HEAT RADIATION

FROM FLARES

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EXECUTIVE SUMMARY

Determination of the levels of thermal radiation emitted from flares is important in facility design. This information is used to site flares and to establish flare stack heights in order that workers and equipment are protected. This information is also used for air dispersion modeling in order to assess the impact to air quality from combustion by-products released from operating flares. Knowledge of the fraction of heat radiated from flares is needed in order to determine thermal radiation levels.

This report briefly reviews and summarizes theoretical and observational relationships for determining the fraction of heat radiated from flares in proximity of a flame. Nine articles are reported in which the fraction of heat radiated in proximity of a flame is determined by theoretically-derived relationships. Two articles are reported in which the fraction of heat radiated in proximity of a flame is determined by empirically-derived relationships. A matrix summarising which parameters have been used to determine the fraction of heat radiated for each of these relationships is shown below. The applicability of these relationships to the general case is limited. The theoretical or empirical conditions for which many of these relationships are based upon are situation-specific. In addition, limited information was provided in many instances on numerous parameters that are known to influence flare heat radiation losses (e.g. stack exit velocity, crosswind velocity, aerodynamics of the flame, etc.).

Relationships for determination of ground-level radiation in proximity of flares are also summarized. In addition, details of field equipment and instrumentation used to measure some of the parameters required for use in the relationships for determining the fraction of heat radiated are reported.

Matrix of parameters used to develop models for the fraction of heat radiated

Citation	Characteristic																	
	Gas					Radiation					Flare					Atmospheric Conditions		
	Mol. weight	Calorific value	Heat of combustion	Mass flow rate	Jet exit velocity	Ground-level radiation	Distance to receiver	Angle between receiver and flare	Net heat release	Fraction of heat intensity transmitted	Total radiative power	Flame temperature	Flame geometry	Emissivity	Atmospheric transmissivity	Wind	Temperature	Humidity
Kent, 1964	✓	✓																
Tan, 1967	✓																	
API, 1969						✓	✓		✓	✓								
Brzustowski & Sommer, 1973						✓	✓	✓	✓									
Leahey et al., 1973									✓			✓	✓	✓				
Ozebring & Sefferman, 1980						✓	✓	✓	✓									
Leahey and Davies, 1984									✓			✓	✓	✓				
Cook et al., 1987			✓	✓					✓		✓		✓	✓				
Chamberlain, 1987						✓		✓	✓				✓		✓			
Cook et al, 1987					✓													
Chamberlain, 1987					✓													

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1 Introduction

Flaring is the combustion process which has been and remains the traditional method for the safe disposal of large quantities of unwanted flammable gases and vapours in the oil industry (Brzustowski, 1976; Dubnowski and Davis, 1983). The primary function of a flare is to use combustion to convert flammable, toxic or corrosive vapors to less objectionable compounds (API, 1990). In Alberta, about 70% of the total gas flared is solution gas, which means that it has been separated from produced oil or bitumen (AEUB, 1999).

Two types of flares predominate in industry: the ground flare and the elevated flare. Ground flares are primarily designed for low release rates and are not effective for emergency releases. Elevated flares, the main focus of this study, can exceed stack heights of 400ft with diameters over 40 inches. The high elevation reduces potential flaring hazards because ground level radiation is lower and better dispersion of gases occurs should the flame be snuffed out (Dubnowski and Davis, 1983).

The Briggs' 2/3 plume rise formula (Briggs, 1969) is the equation most commonly used by regulatory agencies in North America to estimate the rise of hot plumes from both conventional stacks and flares (Leahey, 1979). The equation, based on energy conservation principles, states that:

$$h = \left[\frac{3}{2\beta^2}\right]^{1/3} \frac{F^{1/3} x^{2/3}}{U} \qquad (1)$$

where:

h = plume rise

β = entrainment coefficient = R/h

F = source buoyancy flux

x = downwind distance

U = windspeed at plume height

R = radius of bent-over plume

Whilst the formula has been shown to describe the rise of plumes from conventional stacks well, there is uncertainty in its applicability to flare stacks. This is because, unlike conventional plumes, a flare releases heat at the stack top and can also lose heat by radiation (Davies and Leahey, 1981). In conventional plumes, all of the heat released is assumed to be available for buoyancy (Leahey et al., 1979), but in flares the heat released consists of sensible and radiation heat losses (Leahey and Davies, 1984).

According to Davies and Leahey (1981) Brigg's 2/3 plume rise law can be applied to flares by multiplying equation (1) by the following factor:

$$\lambda = \xi^{2/3}(1-\upsilon)^{1/3} \qquad (2)$$

where: λ = ratio of plume rise from a flare to that from a conventional stack of comparable heat

υ = fraction of total rate of heat release emitted as radiation from the flare

ξ = ratio of value of β which is applicable to stack plumes to that which is applicable to flares

In order to estimate plume rise from a flare using the above equations, a value for the fraction of heat radiated is required.

The fraction of heat radiated is also a critical element in the calculation of heat radiation, in particular ground level radiation experienced in the vicinity of a flare. Most papers reviewed cite staff safety from thermal radiation as the driving force for studying the fraction of heat radiated from flares. Determination of the thermal radiation emitted from flares is important in facility design, since it establishes the required flare siting and stack height in order that workers and equipment are protected.

1.1 Objectives

The purpose of this report was to review scientific literature on heat radiation from flares, focusing on the fraction of heat emitted. Studies relating to determination of the fraction of heat radiated from flares and ground level radiation are presented. In addition, instrumentation and equipment for measuring heat radiated from flares are summarized.

1.2 Scope

In meeting the above objective, a search of scientific literature on heat loss from flares was conducted at the University of Alberta library. Approximately 90 articles of potential use were identified. These included journal papers, conference proceedings, reports and books. Approximately one-third of these articles were ordered from other libraries in Canada and the U.S. A listing of the relevant articles found in the literature search is provided in Appendix 2.

2 Fraction of Heat Radiated

2.1 Definition

The fraction of heat radiated expresses the total radiant power output of a flare as a fraction of the total chemical power input (Cooke et al., 1987b). This dimensionless number allows for the fact that not all of the heat released in a flame can be transferred by radiation (API, 1990).

The fraction of heat radiated is an overall characteristic of the flame, which can be affected by the following variables (Schwartz and White, 1996):

- Gas composition
- Flame type
- State of air-fuel mixing
- Soot/smoke formation
- Quantity of fuel being burned
- Flame temperature
- Flare burner design

The fraction of heat radiated has been referred to in the literature as the F-factor, χ, υ, F and F_s (API, 1990; Cooke et al., 1987b; Leahey and Davies, 1984; McMurray, 1982; Chamberlain, 1987).

The models and relationships of the fraction of heat radiated in this report have been divided into the following categories:

Theoretical relationships, which are based on a deductive or theoretical approach. This involves the use of mechanistic relationships or organising principles.

Empirical relationships, which are based on an inductive or data-based approach. Regression methods are often employed to statistically estimate the relationships between parameters (Chapra, 1997).

2.2 Theoretically derived equations and relationships

Several investigators have defined the fraction of heat radiated using various characteristics of the gas being burned, atmospheric conditions and stack design parameters. Their approaches follow, in chronological order.

2.2.1 Kent, 1964

Kent (1964) provided a theoretical relationship between the fraction of heat radiated and the net calorific value of the gas. The net calorific value of the gas is expressed as Btu per standard cubic foot in which the standard conditions are 14.7 psia and 60°F. The relationship proposed was:

$$f = 0.20\sqrt{\frac{h_c}{900}} \tag{3}$$

and

$$h_c = 50m + 100 \quad \text{for hydrocarbons} \tag{4}$$

$$h_c = \sum nh_c \quad \text{for gas mixtures} \tag{5}$$

where: f = fraction of heat radiated
h_c = net calorific value of combustion
m = molecular weight
n = molar fraction

Assuming that heat release by the flame is uniformly distributed along the length, and discharge is into still air, Kent proposed the following equation for determining the required minimum stack height:

$$H = \frac{\sqrt{L^2 + \frac{fQ}{\pi q_M}} - L}{2} \qquad (6)$$

where:
- H = height of flare stack (ft)
- L = height of flame (ft)
- Q = Total heat release (Btu/hr)
- q_M = maximum radiated heat intensity (Btu/hr-ft^2)

The relationship given in Equations 3 to 5 is derived theoretically from the following values, after Hajek and Ludwig (1960):

- Hydrocarbons, f = 0.4
- Propane, f = 0.33
- Methane, f = 0.2

Kent (1964) provided no experimental validation of the equations and did not explain limitations, implying that the method is applicable to all gases flared and all conditions.

Despite lack of validation, Schmidt (1977) of Shell Development, Texas, used these equations in work on flare design and modeling. In addition, this method for determining the fraction of heat radiated is also used in the Equipment Design Handbook for Refineries and Chemical Plants by Evans (1980). Schwartz and White (1996) say it is important to note that Kent does not consider atmospheric absorption.

2.2.2 Tan, 1967

Tan (1967) proposed a relationship between the fraction of heat radiated and the molecular weight of the gas. Tan derived the following equation for the fraction of heat radiated (Tan, 1967):

$$F = 0.048\sqrt{m} \tag{7}$$

where: m = molecular weight of the flared gas

It would appear that this formula was based entirely on the following three F-factor values and their relationships to molecular weight:

Methane = 0.20 (M = 16)
Propane = 0.33 (M = 44)
Higher molecular weight hydrocarbons = 0.40

Although Tan (1967) does note that Equation 7 is an approximation, no validation of the relationship with experimental data is provided, other than the three F-factors given above. Limitations in the applicability of this equation are not provided.

2.2.3 API, 1969

The American Petroleum Institute Recommended Practice, Section 521 (API, 1969) gives the following equation for calculating the minimum distance from a flare to an object whose exposure must be limited:

$$D = \sqrt{\frac{\tau F Q}{4\pi K}} \tag{8}$$

where: D = minimum distance from the midpoint of the flame to the object being considered, in feet

τ = fraction of heat intensity transmitted

F = fraction of heat radiated

Q = net heat release (lower heating value), in British thermal units per hour (kilowatts)

K = allowable radiation, in British thermal units per hour per square foot (kilowatts per square meter)

Rearranging for the fraction of heat radiated gives:

$$F = \frac{4\pi K D^2}{\tau Q} \tag{9}$$

Tto calculate the F-factor in Equation 9, K becomes actual radiation received at ground level rather than allowable radiation.

Equation 9 ignores wind effects and calculates the distances assuming the centre of radiation is at the base of the flame (at the flare tip), not in the centre. It also assumes that the location where thermal radiation must be limited is at the base of the flare (Stone et al., 1992).

Brzustowski and Sommer (1973) examined this model over a range of D less than one flame length up to about two flame lengths and found that predicted values were remarkably close to the actual values. They suggested that this result shows that this model is quite accurate close to the flame. However, they found that the model could not predict the effect of orientation of receiving surfaces.

Chamberlain (1987) noted that Equation 8 has been successfully applied to onshore refinery flares for many years. However, he indicated that it is of limited use offshore because it can only predict thermal radiation accurately in the far field (the opposite to what Brzustowski and Sommer (1973) reported).

API does not provide experimental evidence validating Equations 8 or 9.

2.2.4 Brzustowski and Sommer, 1973

Brzustowski and Sommer use the point source formula (Equation 8) corrected for the orientation of fixed receiving objects. The fraction of heat intensity transmitted is omitted from their equation.

$$K = \frac{FQ}{4\pi D^2}\cos\theta \qquad (10)$$

where:
- D = minimum distance from the midpoint of the flame to the object being considered (meters)
- F = fraction of heat radiated
- Q = net heat release (lower heating value) (kilowatts)
- K = allowable radiation, (kilowatts per square meter)
- θ = angle between the normal to the surface and the line of sight from the flame centre

rearranging for F yields:

$$F = \frac{4\pi K D^2}{Q\cos\theta} \qquad (11)$$

Brzustowski and Sommer (1973) examined the accuracy of this equation extensively for large windblown flares. The experimental conditions are given in Table 1.

Table 1 – Experimental conditions in Brzustowski and Sommer's validation study

Q *MM Btu/hr*	*lbs. steam* *lb. C_3H_8*	*Tip discharge velocity* *U_j, ft/sec*	*Allowable radiation K* *Btu/hr ft^2*
3.4	0	85	$2.27\times10^4/(D^2)^{0.824}$
3.4	0.33	150	$1.82\times10^4/(D^2)^{0.824}$

They found that the corrected point-source formula (Equation 10) acts much in the same way as the point-source formula (Equation 8), but is less conservative far from the flame. However, the corrected point-source formula is less accurate for predicting radiation to a vertical surface facing upwind or downwind.

Brzustowski and Sommer (1973) state that their results show that the geometrical distribution of radiation is predicted with useful accuracy by the point-source formula, corrected for the orientation of fixed receiving surfaces as required, and that it remains a useful design tool.

2.2.5 Leahey et al., 1979

Leahey et al. (1979) state that when measured data is not available it is necessary to estimate the fraction of heat radiated from a combination of physical principles and curve fitting. They derived a theoretical description of the fraction of heat radiated, based on the geometry of the flame. They represented the flame surface as the frustum of a right cone, as follows:

υ = Heat radiated from frustum surface / heat released in the flame (12)

$$\upsilon = \frac{\varepsilon\sigma T^4 (R+R_0)\sqrt{(L^2+(R-R_0)^2}}{\Delta H R_0{}^2 W_0} \tag{13}$$

where: υ = fraction of heat radiated

ε = emissivity of flare

σ = Stefan-Boltzman constant

T = radiative temperature of the flame (°K)

H = heat of combustion of flared gas

R_o = radius of base of flame 'cone'

R = radius of top of flame 'cone'

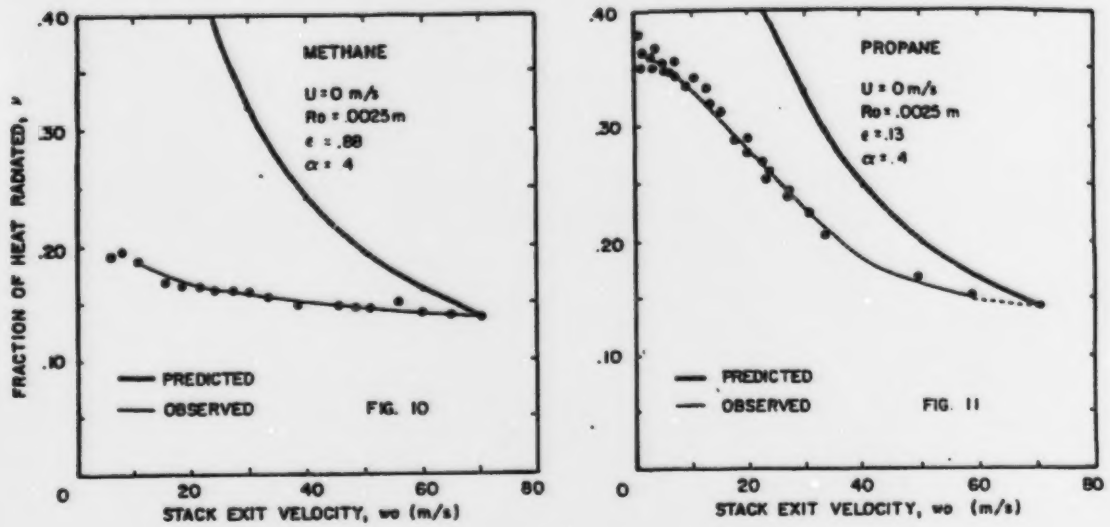
L = length of flame 'cone'

Equation 13 shows the fraction of heat radiated is dependent on the radius and length of the cone, which Leahey et al. (1979) suggest is expected to vary with exit velocity and/or wind speed. Since the F-factor is also dependent upon flame emissivity, Leahey et al. (1979) suggest it will consequently depend on such variables as temperature, soot content and air entrainment.

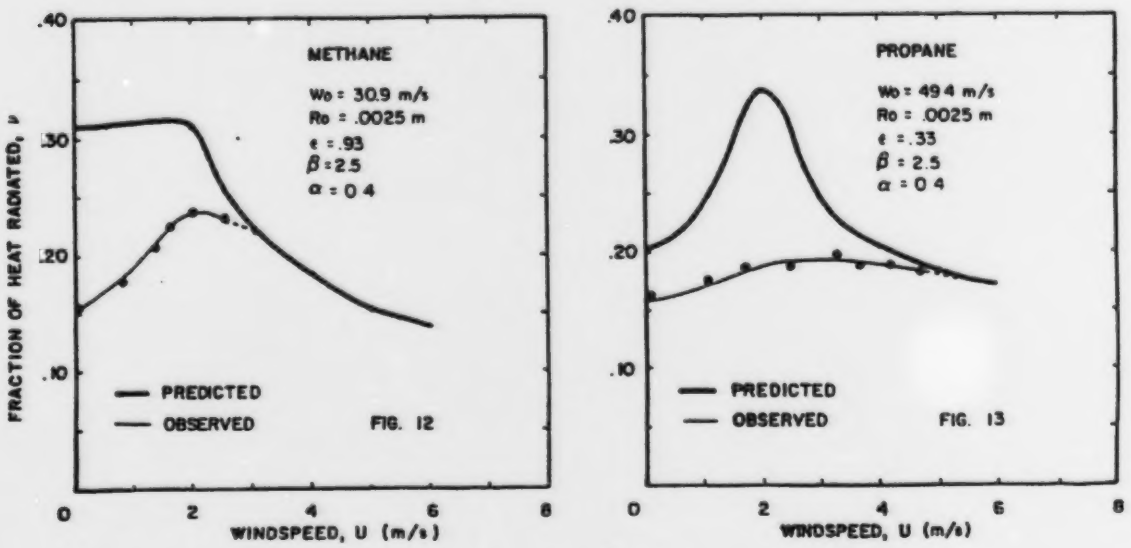
Equation 13 was tested against experimental data. Figures 1 and 2 show a comparison between predicted and observed values of the fraction of heat radiated. The tests were for calm conditions and were given as a function of stack exit velocity. It can be seen that theoretical results tend to overpredict the fraction of heat radiated, and agreement between predicted and observed fractions of heat radiated is better for propane than for methane.

Figures 3 and 4 show a comparison between predicted and observed F-factor values as a function of wind speed. Theoretical values are considerably higher than observed values.

Limitations in the applicability of the theoretical equation for determining the F-factor are not given by Leahey et al. (1979). Limited test conditions are provided on the graphs, but no other experimental conditions were stated.



Figures 1 and 2 – Comparison between the predicted and observed fractions of heat radiated as a function of stack exit velocity for calm conditions (Leahey et al., 1979).



Figures 3 and 4 – Comparison between the predicted and observed fractions of heat radiated as a function of wind speed (Leahey et al., 1979).

2.2.6 Oenbring and Sifferman, 1980

At API's Midyear Refining Meeting, 1980, Oenbring and Sifferman (1980) presented results of several field tests of heat radiation from flares. They calculated the fraction of heat radiated using the API (1969) method, except the factor τ (fraction of heat intensity transmitted) was omitted from the denominator:

$$F = \frac{4\pi K D^2}{Q} \tag{14}$$

where:
- D = distance from flame center to point of interest (ft)
- F = fraction of total heat radiated
- Q = total heat content of the flared gas (Btu/hr)
- K = radiant heat flux from flame (Btu/hr-sq ft)

This method assumed a point-source of radiance, located at one-half the flare flame length. Oenbring and Sifferman (1980) introduced the radiation emission angle, which is the compliment of the angle between the surface of the flame and the line of sight from the observer to the centre of radiance. The relationship is given by:

$$F_{corrected} = F / \cos \alpha \tag{15}$$

where:
- K = radiant heat flux from flame (Btu/hr sq ft)
- F = fraction of total heat radiated
- $F_{corrected}$ = fraction of heat radiated corrected for view angle
- α = radiation emission angle

Oenbring and Sifferman (1980) applied this theoretical idea of F-corrected values to full-scale data to determine whether the radiation emission angle is being observed. The results indicated that the calculated values obtained with the radiation emission angle approach provided a better fit for one set of test data than basic F values and a worse fit for the other data. Therefore, they recommended that a simple point-source approach

without the view angle be used for calculations due to (1) uncertainty regarding the view angle, (2) simplicity of calculations, and (3) the generally nonprecise nature of flare design.

2.2.7 Leahey and Davies, 1984

Leahey and Davies (1984) stated that the heat release from the flared gas stream is partitioned between sensible and radiation heat losses. The fraction of heat lost due to radiation can be estimated from:

$$\upsilon = \frac{Q_r}{Q_s + Q_r} \tag{16}$$

where Q_r is the radiant heat flux.

$$Q_r = A\varepsilon\sigma T_f^{\,4} \tag{17}$$

where:
- υ = fraction of heat lost due to radiation
- A = surface area of the flame
- ε = emissivity of the flame
- σ = Stefan-Boltzman constant
- T_f = absolute radiation temperature of the flame
- Q_s = sensible heat flux

The surface area of the flame is required in order to calculate the fraction of heat radiated. Leahey and Davies (1984) approximated the flame surface area by the surface of a right cone of length l and diameter d, thus:

$$A = \frac{\pi d\sqrt{d^2 + 4l^2}}{4} \tag{18}$$

Leahey and Davies (1984) conducted experiments to validate their equations. Flame length and diameter were determined from photographs and flame temperature was measured using a portable infrared thermometer. Radiated heat values were calculated based on the temperature measurements. Oil of molecular weight approximately 10 was added to the flare and approximately 50% of it was found to have been burnt off. Observations from their flame tests are presented in Table 2. No other experimental parameters were provided, for example wind speed, stack diameter etc.

Table 2 – Flame parameters observed for each test and resulting fraction of heat radiated (Leahey and Davies, 1984).

Date	*Time*	*Fuel flow rate* (m^3s^{-1})	*M.W.*	*Flame dimensions*			*Flame temp.* (°C)	Q_r *(Mw)*	*Fraction of heat radiated*
				Length (m)	*Diameter (m)*	*Area* (m^2)			
13 Feb. 1980	1415	0.0072	4.6	6.6	2.2	23.1	1150	5.4	0.47
13 Feb. 1980	1600	0.0072	4.6	8.8	2.0	27.8	1150	6.5	0.65
14 Feb. 1980	1000	0.035	2.2	5.7	1.7	16.3	1150	3.8	0.52
10 June 1980	1045	0.072	5.1	3.9	1.6	8.8	1450	4.4	0.61
10 June 1980	1330	0.072	5.1	6.6	1.4	9.3	1550	5.8	0.55
10 June 1980	1545	0.044	3.1	7.1	1.4	15.4	1500	8.6	0.57
10 June 1980	1630	0.062	4.4	7.2	1.6	15.7	1500	8.8	0.44
11 June 1980	1250	0.060	4.1	6.8	1.7	10.4	1400	4.6	0.42
11 June 1980	1600	0.067	4.5	10.4	1.5	21.0	1450	10.5	0.69
								Average	0.55

2.2.8 Cook et al., 1987a

Cook et al. (1987a) stated that, since predictions of incident thermal radiation are based on an assumed fraction of heat radiated χ, spatially averaged emissive power data can be used to calculate χ on the assumption that a flare radiates as a uniform diffuse surface emitter. They proposed the following equations:

$$P = EA_f \tag{19}$$

$$P = \chi Q = \chi m_j \Delta h_c \tag{20}$$

where:

P = total radiative power (W)

E = Emissive power (Wm^{-2})

A_f = Flame area (m^2)

χ = fraction of heat radiated (dimensionless)

Q = total heat release rate (W)

m_j = mass flow rate of gas exiting stack (kg^{-1})

Δh_c = heat of combustion (Jkg^{-1})

Rearranging for the fraction of heat radiated gives:

$$\chi = \frac{P}{Q} = \frac{P}{m_j \Delta h_c} \tag{21}$$

Results of the Cook et al. analysis are shown in Figure 5 and the test conditions are given in Table 3. The total radiative power was calculated from Equation 19. The fraction of heat radiated was derived from this figure by dividing the ordinance by the abscissa. Values of the fraction of heat radiated varied from 0.017 to 0.344, the mean value over all tests being 0.187 (Cook et al., 1987a).

Table 3 – Range of conditions considered in the field scale experiments (Cook et al., 1987)

d/mm	Stack height /m	Number of experiments	u_j/ms^{-1}	m_j/kgs^{-1}	$Re_j \times 10^{-6}$	u_∞/ms^{-1}	u_j/u_∞	$R \times 10^{-3}$	ζ	Figure symbol
51	2.0	1	402	8.4	20.3	4.0	100.4	84.2	3.3	◇
102	2.0, 3.0	21	172–402	1.0–24.0	1.2–28.9	1.5–13.0	19.1–114.5	0.2–47.3	2.5–5.2	○
146	2.0	3	402	13.1–60.3	11.0–50.7	2.1–6.2	64.8–191.2	16.6–81.4	3.5–6.2	△
152	3.0	9	241–401	3.3–27.3	2.5–21.5	1.0–8.0	47.5–386.6	2.0–113.4	3.1–5.2	□
303	11.8	10	89–384	4.9–25.2	1.9–10.0	3.5–8.5	20.3–109.6	0.2–8.7	3.6–8.4	●
385	16.0	8	135–391	11.6–81.7	3.6–25.1	4.4–6.9	22.2–88.8	0.3–10.4	4.2–6.0	■
590	12.0	5	240–378	50.1–88.7	10.4–18.4	1.8–3.5	45.1–188.8	1.3–24.9	5.1–6.0	△

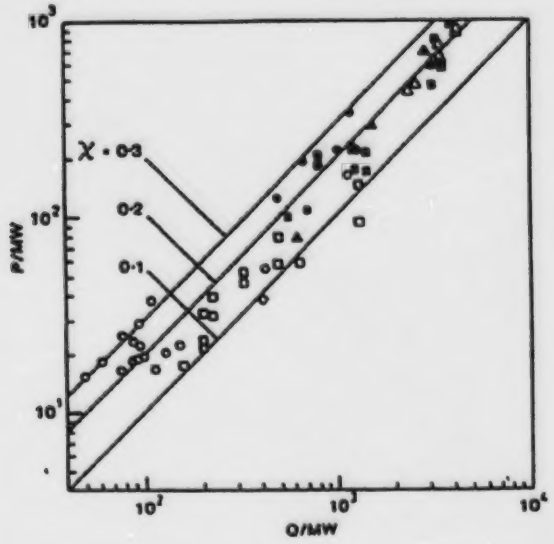


Figure 5 – Variation of total radiative power with total heat release rate, derived using the diffuse surface emitter assumption (key to symbols indicated in Table 3 on the previous page) (Cook et al., 1987).

In tests, the spatially averaged surface emissive power data obtained from both cross-wind and downwind positions was approximately constant with increasing gas flow rate, a mean value over all tests of 239 kWm^{-2} having been obtained.

Cook et al. (1987a) do not indicate the limitations of their method, nor do they provide a validation by comparing predicted verses actual data.

2.2.9 Chamberlain, 1987

Chamberlain (1987), working for Shell Research in Thornton, England, produced models for predicting flare flame shape and radiation field. Chamberlain idealized the flame as a frustum of a cone, and defined the fraction F_s of the net heat content of the flame that appears as radiation from the surface of this solid body in terms of surface emissive power.

$$F_s = \frac{Q}{SEP \cdot A} \tag{22}$$

where: SEP= surface emissive power (kW/m^2)

F_s = fraction of heat radiated from surface of flame

A = surface area of frustum including end discs (m^2)

Q = net heat release (kW)

To calculate the fraction of heat radiated, each parameter of the equation must first be determined. The flame surface area, A, including the end discs was given by:

$$A = \frac{\pi}{4}\left(W_1^2 + W_2^2\right) + \frac{\pi}{2}\left(W_1 + W_2\right) \times \sqrt{R_L^2 + \left(\frac{W_2 - W_1}{2}\right)^2} \tag{23}$$

where: W_1 = width of frustum base (m)

W_2 = width of frustum tip (m)

R_L = length of frustum (flame) (m)

The surface emissive power was calculated by:

$$SEP = \frac{q}{VF \cdot \tau} \tag{24}$$

where: q = radiation flux at any point (kW/m^2)

VF = view factor of the flame from the receiver surface

τ = atmospheric transmissivity

The view factor depends on location of the flame in space relative to the receiver position. It is calculated from a two-dimensional integration performed over the solid

angle within which the frustum is visible from the receiving surface. Thus, the view factor for an elemental receiver area dA_2 of emitter of area A_1 is given by:

$$VF = \int_{A_1} \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} dA_1 \qquad (25)$$

where:
- θ_1 = angle between local normal to surface element dA_1 and the line joining elements dA_1 and dA_2
- θ_2 = angle between local normal to surface element dA_2 and the line joining elements dA_1 and dA_2
- r = length of line joining elements dA_1 and dA_2
- A_1 = visible area of emitting surface (m^2)
- A_2 = receiver surface area (m^2)

The two-dimensional integral can be reduced to a single, contour integral using Stoke's theorem. For the frustum of a cone, the single integral is then amenable to analytic solution.

Large-scale field trials were conducted to validate the radiation equations. Details of the tests conducted are given in Table 4. Measurements were made of the radiant flux emitted by the flame and incident on land radiometers located over as large a range of viewing factors as practical and usually in the far field, i.e. greater than one flame length from the flame centre. Flame shape was recorded using photography and wind speed, humidity and ambient temperature were measured. Surface emissive power and fraction of heat radiated from the flame were derived from the incident radiation flux measurements and synchronous flame shape using Equations 22 and 24.

Equations 22 to 24 were used to calculate radiation levels at selected radiometer locations, which were then compared with the measured values. The comparison enabled estimates to be made of the accuracy of the model in ranges of conditions where no measurements are available. It was found that in the far field, where the measured

radiation is less than 4 kW/m^2, agreement was good; in many cases the discrepancy is less than 10%. Near field measurements showed that reasonably good agreement was maintained for downwind and cross-wind radiometers but there was a tendency to underpredict in the upwind locations. Good predictions of ground-level radiation using this model suggest that the value calculated for the fraction of heat radiated is reasonable.

Chamberlain concluded that this model describes the radiation field around a flare well and that compared to the point-source models, this model has a firmer theoretical basis and a more realistic geometrical representation.

2.3 Empirically derived equations and relationships

Only a few researchers have attempted to define the fraction of heat radiated using an equation derived empirically. These approaches are discussed below.

2.3.1 Chamberlain, 1987

Chamberlain (1987) conducted a large number of flare tests in order to validate theoretical and empirical models that he had developed over several years. This included 98 laboratory tests in wind tunnels and 31 large scale trails, 10 of which were at an on-shore oil and gas production installation in Holland, 6 at an off-shore oil platform in the North Sea and the remainder at a test site in Cumbria, UK. Details of the tests conducted are shown in Table 4.

Chamberlain (1987) plotted gas exit velocity verses fraction of heat radiated from the flame surface and found a correlation. As shown in Figure 6, all the low velocity tests and high velocity 8" and 12" tests collapse into a single curve.

Table 4 – Range of Parameters Covered by Flare Tests (Chamberlain, 1987).

		Large scale trials			
	Laboratory	1	2	3	4
# tests	98	5	5	6	15
Exit diameter, m	0.006-0.022	0.6	0.152	1.07	0.152, 0.203, 0.305
Exit velocity, m/s	15-220	14-51	108-263	2.5-75.5	171-554
Mach number	0.06-0.9 (C_3H_8)	0.03-0.12	0.23-0.57	0.06-0.19	0.41-1.53
	0.08-0.2 (CH_4)				
Mol. weight	16-44	18.6	17.25	19.6-21.1	16.94
Wind speed, m/s	2.7-8.1	5-9	6-10	7-8	3-13
Other	Angled jets				

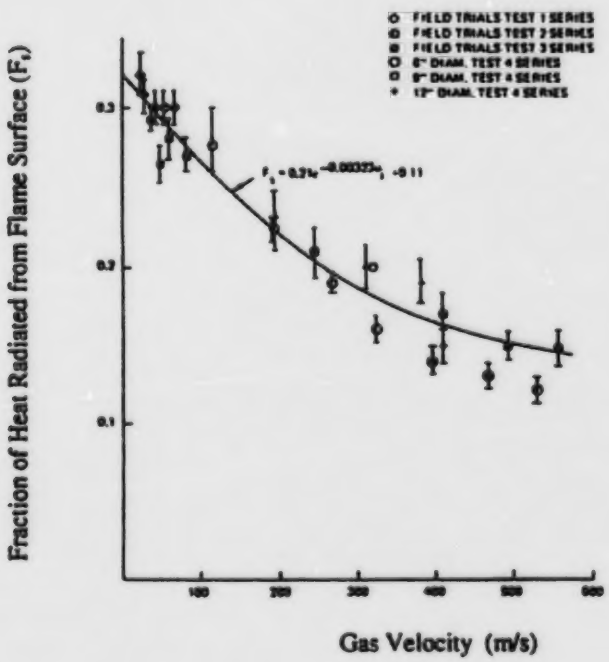


Figure 6 – Fraction of heat radiated from the flame surface verses gas velocity for pipe flares. The vertical bars represent the standard deviation at each point (Chamberlain, 1987).

Chamberlain described the correlation between fraction of heat radiated and gas exit velocity with the following equation:

$$F_s = 0.21e^{-0.00323u_j} + 0.11 \qquad (26)$$

where: u_j = gas velocity (m/s)

F_s = fraction of heat radiated from flame surface

The F_s factor for high velocity 6" diameter tests fall below the curve because the flames are smaller and spectrally different from those at higher flow rates. The correlation, therefore, referred to large flares typical of offshore flare system design flow rates. For small flames at high velocity, the equation will overpredict F_s, and flare systems designed for these cases will be conservative unless a more appropriate value of F_s is used.

2.3.2 Cook et al., 1987b

Cook et al. (1987b) of British Gas, Solihul, England, presented a model that was based on the experimental data obtained in fifty-seven field scale experiments.

Cook et al. (1987b) examined the effect of jet exit gas velocity on f-factor values derived from field-scale experiments, the results being shown in Figure 7. The results in this figure were obtained from spatially averaged emissive power data on the assumption that a flare radiates as a diffuse surface emitter, and from received radiation data assuming isotropic single point source emission. Only those values of the fraction of heat radiated derived from radiometers positioned downwind of a flare are shown since in any given experiment these radiometers were usually located closer to a flare than upwind and cross-wind instruments.

Cook et al. (1987b) found no relationship evident between the fraction of heat radiated and wind speed, despite the data of Brzustowski et al. (1975) indicating otherwise.

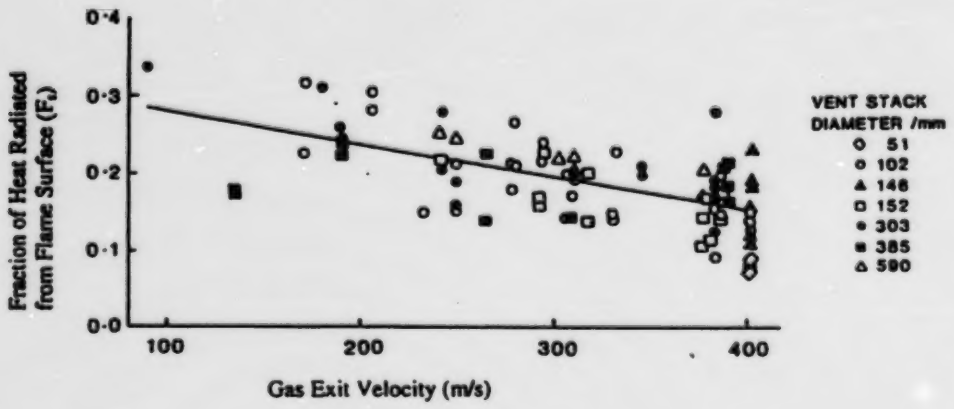


Figure 7 – Effect of jet exit velocity on fraction of heat radiated (Cook et al. 1987)

Cook et al. (1987b) provided the following correlation between fraction of heat radiated and the jet exit velocity:

$$X = 0.321 - 0.418 \cdot 10^{-3} u_j \qquad (27)$$

where: X = fraction of heat radiated

u_j = jet exit velocity (m/s)

Cook et al. (1987b) did not provide a statistical analysis describing the goodness of fit between Equation 27 and the experimental data points. It can be seen that the data is fairly scattered.

Cook et al. used Equation 27 in their radiation prediction model (incorporating approximately 10 other equations). The complete model was validated by comparing predictions with measured values of incident radiation obtained in 57 field scale experiments. It was found that over 80% of all predictions were within ±30% of the measurements. However, this information does not help in validating Equation 27 for the fraction of heat radiated.

2.4 Values quoted in the literature

A considerable number of papers provide single values for fraction of heat radiated, usually without stating the operating parameters and gases for which they are applicable.

Leahey and Davies (1984) conducted tests at a Vulcan, Alberta, gas plant in 1980. The flare stack used was 32m in height and two series of tests were conducted. The first tests in February used a gas composed of 40% carbon dioxide, 50% methane, 9.8% ethane and propane and 0.2% hydrogen sulphide. The second tests in June used approximately 90% carbon dioxide, 8% methane and 1% hydrogen sulphide (the missing 1% is not defined). The fraction of heat radiated was determined using equations defined in Section 2.2.7. It was found that an average of 55% of the available heat was radiated and only 45% contributed to plume rise with a range of values from 42 to 69% for the fraction lost.

The value of 0.55 for the fraction of heat radiated from a flare is consistent with values of about 0.5 estimated by Oenbring and Sifferman (1980a) for heavy gases. Oenbring and Sifferman's value was determined from ground-based radiation measurements together with the assumption that all flared products were completely combusted.

Reed (1981) correlated the weight ratio of hydrogen to carbon in flare gas with the fraction of heat radiated, although only field observation values were provided, rather than an equation. This approach recognises that greater carbon content can lead to increased soot in the flame, but it fails to recognise that enhanced fuel-air mixing can mitigate soot formation (Schwartz and White, 1996).

Without stating gas characteristics, stack dimensions or test conditions, Reed (1981) and Evans (1974) noted that field observations confirm that when the hydrogen to carbon (H/C) ratio-by-weight of flared gases was greater than 0.5, the fraction of heat radiated was close to 0.075. As the H/C ratio reacheed 0.33, the fraction of heat radiated was 0.11. The fraction of heat radiated was maximum at 0.12 when the H/C ratio wass approximately 0.25 and as the H/C ratio decreased there was a drop in the fraction of heat radiated to 0.07 at 0.17 H/C.

Brzustowski and Sommer (1973) measured F factors for methane and propane, relative to the jet exit velocity, and their results are shown in Figure 8.

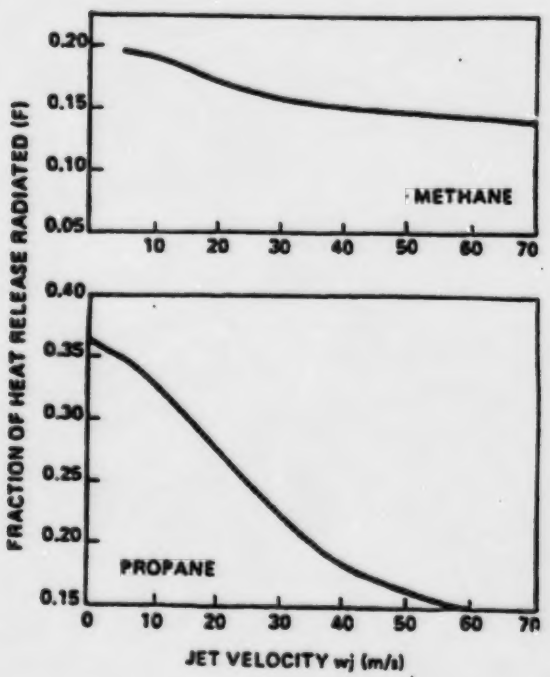


Figure 8 - Effect of jet exit velocity on the fraction of heat radiated in the absence of a cross-wind (taken from Barnwell and Marshall, 1984).

The results shown in Figure 8 are based on wind tunnel experiments and suggest F factors of less than 0.2 for methane rich gases (Barnwell and Marshall, 1984).

Becker and Laing (1981) proposed the following F factors, without stating limitations or validation:

Methane	0.18
Ethane	0.25
Propane	0.3

Zabetakis and Burgess (1961) reported the following values of F for a number of gases, as cited in Brzustowski and Sommer, 1973:

Hydrogen	0.17
Ethylene	0.38
Butane	0.30
Methane	0.16
Natural Gas	0.23

It is not indicated how these values were determined.

Sunderland et al. (1994) conducted laboratory-scale tests on C_2H_2/N mixtures with combustion in coflowing air at 0.125-0.250 atm., producing visible flame lengths of 50mm. They reported radiative heat loss fractions of 29 to 34%.

Brzustowski and Sommer (1973) conducted experiments to study the variation in F-factor with steam and discharge velocity. They found that increasing the discharge velocity decreased F but concluded that the precise effects of steam addition in full-scale flares could not be assessed with the data available. They also performed experiments to see how radiation falls on a surface which is exposed to the flame end on, with all calculations using the corrected point-source model (Equations 10 and 11, Section 2.2.4). They found that the model under-predicted the value of F by up to 60% and hence K for surfaces which view the flame end on. They suggested the corrected point-source model be retained for its convenience, but a higher effective F should to be used for calculations of K to surfaces which view the flame at close proximity end on.

Brzustowski and Sommer (1973) stated that the API RP 521 F-factor approach is somewhat conservative for flares discharging at high velocity. However, they noted that since no systematic data are available to document this trend, F values listed in the API RP 521 should continue to be used. Values given in the API RP 521 (API, 1969) are:

Methane (maximum value in still air)	0.16
Methane	0.20
Heavier gases than methane	0.30

Appendix 1 further summarizes the individual values for the fraction of heat radiated from flares cited in the literature. The applicability of these values for the general case is limited. The theoretical or observational conditions in which many of these values were derived were situation-specific. In many instances limited information was provided on numerous parameters known to influence flare heat radiation losses (e.g. exit gas velocity, gas exit diameter, crosswind speed etc.).

3 Equations and Relationships for Measuring Ground Level Radiation

It is also important to know the radiation experienced in the vicinity of a flare for health and safety reasons. The following sections present a number of equations that exist in the literature for calculating ground level radiation around a flare.

3.1 API, 1990

The following equation, modified from Hajek and Ludwig (1960), may be used to determine the distance required between a location of atmospheric venting and a point of exposure where thermal radiation must be limited. The equation, which appears to be the most widely used equation, assumes a point source for the radiation at the centre of the flare.

$$D = \sqrt{\frac{FQ}{4\pi K}} \tag{28}$$

where: K = allowable radiation (Btu/hr/ft^2)

F = fraction of heat radiated

Q = total heat content of the flared gas (Btu/hr)

D = minimum distance from the midpoint of the flame to the object being considered (ft)

Equation 28 is cited in API RP 521 as the recommended equation for calculating spacing around flares when the safety criterion is expressed in terms of a limit on the value of K. However, the geometry the API model might not be accurate for large windblown flares, as stated by Brzustowski and Sommer, 1973.

3.2 Brzustowski and Sommer, 1973

A modification of the API equation to incorporate the view angle was proposed by Brzustowski and Sommer (1973):

$$K = \frac{FQ}{4\pi D^2}\cos\theta \qquad (29)$$

where: $\bar{D}$ = minimum distance from the midpoint of the flame to the object being considered (meters)

F = fraction of heat radiated

Q = net heat release (lower heating value) (kilowatts)

K = allowable radiation, (kilowatts per square meter)

θ = angle between the normal to the surface and the line of sight from the flame centre

Brzustowski and Sommer (1973) state that all of their evidence suggested that the corrected point-source model, with the flame centre located halfway along the flame, is a valid tool. They also stated that the model could be counted on to predict the radiant heat flux K from large wind-blown flares with useful accuracy over a wide range of practical conditions.

3.3 McMurray, 1982

Figure 9, was presented by McMurray to illustrate the fit of various models reported here to actual data. One of the lines shows the fit of the API equation to experimental data. A reasonable fit was obtained in the far field, but predictions in the near field are poor.

McMurray presented a model called the integrated mixed source model (IMS model), also shown in Figure 9, which is based on regression analysis and predicted radiation over the whole of the radiation field.

These models are described below.

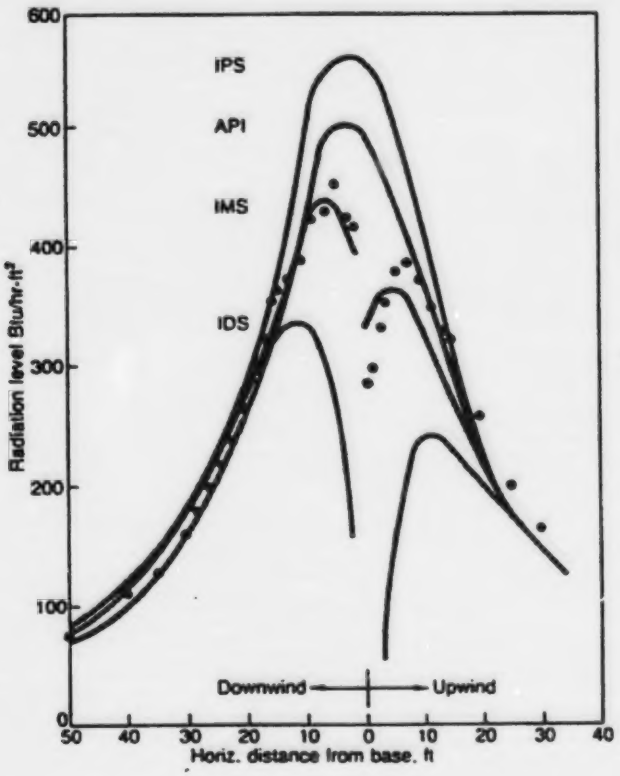


Figure 9 – Fit of various models to data (INDAIR flare, $Q = 2.45 \times 10^7$ Btu/hr, L = 17 ft, 9863 cfh propane). For the IMS model, F = 0.0985 and a = 0.54 (McMurray, 1982).

The IPS model assumes a long thin flame comprised of a series of point sources each radiating over 4π steradians. This gives:

$$K_{IPS} = \frac{Fq}{4\pi L}\int_0^L \frac{1}{d^2}\cdot dl \qquad (30)$$

where: K = radiative flux (Btu/hr-ft^2)

F = fraction of heat radiated

q = net heat release from the flame (Btu/hr)

L = overall flame length (ft)

d = distance from flame element to receptor (ft)

l = curvilinear flame length (ft)

This equation assumes that the flame itself is completely transparent to radiation and one point source will not interfere with another.

The IDS model assumes the flame is completely opaque so that the radiation emanates from the surface of the flame envelope. The diffuse surface radiation equation is:

$$K_{IDS} = \frac{Fq}{\pi^2 L}\int_0^L \frac{\sin\beta}{d^2}\cdot dl \qquad (31)$$

where: β = angle between tangent to flame and line of sight to receptor

Application of these models to data (Figure 9) shows that neither of the models provided a good description of the radiation field. The IPS model overpredicted in the near field and the IDS underpredicted near the flare.

McMurray (1982) combined these models to provide a description of the radiation system, as follows:

$$K_{IMS} = aK_{IPS} + (1-a)K_{IDS} \qquad (32)$$

where: a = constant

These methods do not require the flame length to be measured. Instead, the flame length was correlated to the total heat content of the flared gases as follows:

$$L = cQ^b \tag{33}$$

where: L = overall flame length (ft)
Q = total (gross) heat release from the flame (Btu/hr)
c = constant
b = constant

which may be transformed to give:

$$\log L = c + b \log Q \tag{34}$$

By substituting log L with Y and log Q with X in the standard form:

$$Y = c + bX \tag{35}$$

values for c and b are given for n data points by:

$$b = \frac{[XY] - ([X][Y]/n)}{[X]^2 - ([X]^2/n)} \tag{36}$$

$$c = [Y]/n - (b[X]/n) \tag{37}$$

The two unknown parameters in the IMS model are F and a. McMurray (1982) proposed the following method for calculation of these parameters:

Calculate the expected radiation levels using both IPS and IDS models with an assumed F-factor of 1.0. This obviously gives very high levels compared to the measured values

and these are represented by K_{IPS} and K_{IDS}. The next step is to use a regression analysis formula of the form:

$$Y = cX_1 + bX_2 \tag{38}$$

Where: Y = the measured values
X_1 = the K_{IPS} values
X_2 = the K_{IDS} values

The correlated values for F and a are given by:

$$F = c + b \tag{39}$$

$$a = \frac{c}{c+b} \tag{40}$$

where:

$$c = \frac{[X_2^2][X_1Y] - [X_1X_2][X_2Y]}{[X_1^2][X_2^2] - [X_1X_2]^2} \tag{41}$$

$$b = \frac{[X_1^2][X_2Y] - [X_1X_2][X_1Y]}{[X_1^2][X_2^2] - [X_1X_2]^2} \tag{42}$$

McMurray (1982) stated that the IMS model represented an improved method to predict radiation from flares. However, it does not allow for variation in heat release along the length of the flame.

Chamberlain (1987) stated that McMurray's models have been used successfully but notes that there is considerable uncertainty on how these models perform outside their range of correlation.

3.4 De-Faveri et al., 1985

De-Faveri et al. (1985) stated that thermal radiation from flares is more accurately determined when the flame source is considered as a surface rather than as a point-source or as a uniform distribution along the flame axis.

The flame was assumed to be a radiating surface:

$$dp = \left(\frac{\sigma f T^4}{4\pi D^2_{x,y}} \right) \cos\theta dA \tag{43}$$

The sight factor, cos θ, (Figure 4) can be expressed as:

$$\cos\theta = \frac{(z - \bar{z})}{D_{x,y}} \tag{44}$$

and

$$D_{x,y} = \sqrt{(z - \bar{z})^2 + (\bar{x} - x)^2} \tag{45}$$

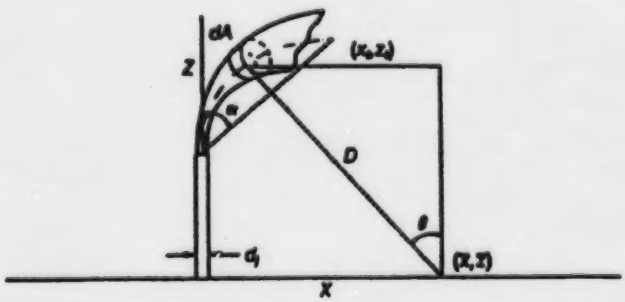


Figure 10 – Diagram of the flare flame (De-Faveri et al., 1985).

Furthermore:

$$dA = \pi \phi ds \tag{46}$$

where:

$$\phi = 2x^{0.4}(d_j R)^{0.6} \tag{47}$$

These equations yield the following heat flux:

$$q = (4.24)(10^{-8})(d_j R)^{1.06} fT^4 \int_0^{x_1} \frac{Ax^{0.36} + h - \bar{z}}{x^{0.06}\left\{(Ax^{0.36} + h - \bar{z})^2 + (\bar{x} - x)^2\right\}^{2/3}} dx \tag{48}$$

where:

	q	=	Thermal radiation in a given point (Kcal/s.m^2)
	f	=	Fraction of radiant heat release
	D	=	distance from a given point (m)
	T	=	temperature (K)
	x	=	downstream distance (m)
	h	=	height of flare stack (m)
	z	=	cross-stream distance (m)
	d	=	diameter of flare stack
	θ	=	sight angle
	σ	=	Stefan-Boltzman constant
	p	=	density (Kg/m^3)

Results from the approaches of Brzustowski and Sommer (1973), API (1969) and Kent (1964) compared well with results from De-Faveri et al's surface approach at distant points from the flare but differ significantly in the region near the flare. Figure 11 (De-Faveri et al., 1985) compares the results of a working example for calculating the ground level radiation using different approaches. De-Faveri et al. stated that the maximum

predicted by the radiating surface model was about 50% lower than the maximum calculated by Brzustowski and Sommer (1973) and 30% lower than API (1969).

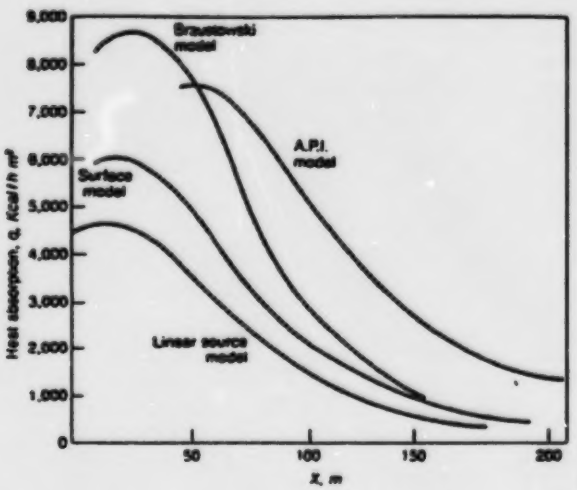


Figure 11 – Comparison of the results of determination of ground level radiation between three approaches for calculating radiation intensity (De-Faveri et al., 1985).

3.5 Shell U.K., 1997

Shell Research, UK, developed a suite of models (CFX-FLOW3D and CFX-Radiation) and corresponding sub-models designed to model turbulent high-pressure jet flames (Johnson et al. 1997). Reliable predictions were obtained for under-expanded sonic structure, jet flame trajectory, flame lift-off position, flame temperature, soot formation and external thermal radiation. The models can be used to predict heat fluxes to objects inside the flame. For information on these models, Dr A. D. Johnson (Shell Research and Technology Centre, Thornton, PO Box 1, Chester, CH1 3SH, UK) can be contacted.

4 Instrumentation Guidelines and Experience

Regardless of the method and equations chosen for measuring radiation or the fraction of heat radiated, many of the same parameters still have to be measured. The following sections outline some of the equipment that can be used to make such measurements.

4.1 Ground level radiation

Radiation can be measured directly using a calibrated thermopile or indirectly by measuring the temperature of a blackened plate thermocouple. McMurray (1982) used a thermopile device (or radiometer), which gives a millivolt output that is directly converted to radiative flux, since more accurate results are obtained. When used in the field, a window of infrared transparent material, such as Irtran 2, may be incorporated to minimise wind effects. These devices can measure radiation fluxes up to about 4 000 Btu/hr-ft^2. Their only drawback is cost. The output from a radiometer fluctuates, so a time-averaged output is needed.

Blackened plate thermocouples consist of a small thin disc of metal to which a thermocouple is brazed, and the whole unit is painted black to provide a highly absorptive surface.

Bjorge and Bratseth (1995) measured radiation heat flux during tests in Norway using Medtherm 64-1-20T heat flux sensors (Schmidt-Boelter type). Each sensor had a window of CaF_2 to protect the sensor and eliminate direct convective heat transfer. The sensors were factory calibrated and the calibration was checked before and after each measurement series. The temperature limit of the sensors was 200°C, response time less than 1.5 seconds and accuracy ±3%.

Cook et al. (1987a) used six Land RAD/P/W slow response (3 seconds) thermopile type radiometers, with a wide circular field of view (90°), to measure the incident thermal radiation at positions around a vent stack. In addition, a narrow angle fast response

(approximately 50 ms) radiometer, developed in-house, was manually scanned along the major axis of the flares from a cross-wind position during a limited number of tests.

Brzustowski and Sommer (1973) used two radiometers to measure the radiant heat flux. One was mounted crosswind to the flare and the other on a line 60° downwind.

4.2 Gas temperature

Temperatures have long been measured in flames and therefore accurate and rapid techniques are available. The most common is the bare thermocouple, a standard instrument that is readily available, which has a response time of less than one millisecond. EERC (1983) suggested that coated thermocouples should be used to avoid catalytic reaction on the metal surface of the instrument. In regions where the temperatures are below 1 300°F, unshielded thermocouples coated with high-temperature cement can be used.

Radiation losses from the thermocouple cause an error in the measured flame temperature. These losses can be corrected by calculation, electrical compensation or by reduction of radiation loss. The most common method for larger flames is to use a suction pyrometer, which increases the convective heat transfer to the thermocouple (EERC, 1983).

Davies and Leahey (1981) assessed flame temperatures using a portable infrared thermometer designed for non-contact measurement of flame and hot gas mixtures containing CO_2. This instrument featured a narrow band pass filter centered on 4.5 microns which allows measurement of flame temperature without interference from cold CO_2 or other normal atmospheric gases.

4.3 Gas exit velocity

In order to calculate local mass fluxes, the velocity distribution in the flare flow field has to be determined. EERC (1983) considered five devices for measuring velocity: pitot,

laser doppler velocimeter, balance pressure probe, turbine meter and hot wire anemometer.

The pitot (Prandtl) probe has a velocity range of 8-200 ft/sec, an uncertainty greater than 25%, a response time of 0.1 sec and a spatial resolution of a fraction of an inch.

The laser doppler velocimeter (LDV) could theoretically be used to measure velocities of gases exiting from flare flames (Durst et al., 1976). However, EERC (1983) suggested LDV's should not be used as the primary technique to measure velocities because they are complex, geometrically difficult to use in large flames, have undefined errors and are expensive.

Hot wire anememetry has been successfully used to measure velocities in many cold isothermal, clean flows. However, the errors associated with the use of hot wire to measure velocities in intermittently fluctuating flames are unknown, and could be very large. In addition, maintaining the integrity, cleanliness and stability of the probe in a large turbulent flame is impossible (EERC, 1983).

A unique air flowmeter using a combination sensor that is based on flow induced differential pressure is commercially available and was used by Seigal (1980) in a flare study. The accuracy of this type of probe is unknown at velocities below 17 ft/sec, as is its applicability in a hot and fluctuating environment (EERC, 1983).

EERC (1983) recommended the turbine meter because it is "rugged, has acceptable spatial resolution and is capable of measuring a range of velocities". The turbine meter used in an EERC study had a three-inch diameter head and it responded linearly over the range of 1 to 30 feet per second.

4.4 Fuel flow rate

Ultrasonic instruments are the preferred method for measuring flare gas flow rate (Strosher et al., 1998). Ultrasonic instruments do not obstruct the flow and the sensing element does not cause a pressure drop. Panametrics Model 7168 flowmeter is specifically marketed for measuring flare gas flow rate with an ultrasonic transit-time technique.

Other instruments that may be suitable for measuring flowrate include orifice plate meters, vortex meters and venturi meters (Strosher et al., 1998).

4.5 Gas composition

Gas chromatography is the standard method in the laboratory for determining the composition of gas samples. Compact gas chromatographs have been developed recently which are capable of analyzing flare gases containing vapour phase hydrocarbons up to C5. For example, Microsensor Technology Inc. is a company that sells compact gas chromatographs and has models specifically for natural gas analysis. The sample analysis time is less than 5 minutes (Strosher et al., 1998).

4.6 Flare flame size

Flare flames continuously change in time and space. Photography and movies and video can be used to produce records of the global and local flame structures.

Still photographs primarily record the overall flare characteristics such as length and orientation. Since the camera is mounted away from the control room, the camera must have an automatic film winder and a remote activation shutter.

High-speed movies can record the formation and life of individual flare eddies. A speed of 500 to 1000 frames per second is sufficient to track the moving eddies (EERC, 1983).

A video recorder is less expensive than high speed film production, and will allow monitoring and evaluation of the flare flame. Video cameras sensitive to infrared light may be of use also.

Oenbring and Sifferman (1980a) shot movies of their flare testing but substantiated the observed values with slides and theodolite measurements of the coordinates of the flame tip.

4.7 Ambient conditions: wind, temperature and humidity

Wind speed and direction can be measured at an elevated height using a lightweight cup anemometer and a wind vane. Ambient air temperature and relative humidity can be recorded using a sensor housed in a Stevenson's screen. Atmospheric pressure can be recorded using a 1 bar absolute pressure transducer (Cook et al., 1987a).

Wind direction and speed information in tests by Davies and Leahey (1981) were obtained from both minisonde releases and camera photographs. Photographs of the plume were also used to determine the wind direction and speed at plume height. The wind direction was determined by evaluating photographs taken simultaneously by two movie cameras whose axis were at approximate right angles with each other. Once the wind direction was determined, the wind speed at plume height was calculated by looking at the transit of a unique plume element over a period of time.

5 Conclusion

Nine articles summarised in this report define the fraction of heat radiated from flares (the f-factor) in terms of theoretically-derived relationships and two papers define the fraction of heat radiated from flares in empirically-derived relationships. Another fifteen papers reported single f-factor values determined in lab-scale or field-scale tests.

The table provided in the Executive Summary is a matrix that summarises the parameters used to determine the fraction of heat radiated for the eleven relationships reported here. The early approaches assume that the fraction of heat radiated is a property of fuel only and do not account for variation of operating parameters such as stack exit velocity, cross-wind velocity and aerodynamics of the flame, etc.

The applicability of these relationships to the general case is limited. The theoretical or observational conditions in which many of these relationships are based upon are situation-specific. In addition, in many instances limited information was provided on numerous parameters (i.e. those mentioned above) known to influence flare heat radiation losses.

6 References

API (1969). 'Guide for Pressure-Relieving and Depressuring Systems - American Petroleum Institute Recommended Practice 521'. Washington, D.C.: American Petroleum Institute, Edition 1, 1969.

API (1990). 'Guide for Pressure-Relieving and Depressuring Systems - American Petroleum Institute Recommended Practice 521'. Washington, D.C.: American Petroleum Institute, Edition 3, 1990.

Alberta Energy and Utilities Board (AEUB) (1999). 'Upstream Petroleum Industry Flaring Guide', Guide Number 60, July 1999.

Barnwell, J. and Marshall, B. K. (1984). 'Offshore Flare Design To Save Weight', American Institute of Chemical Engineers Meeting, November 1984, San Francisco, California.

Becker, H. A. and Laing, D. (1981). 'Total Emission of Soot and Thermal Radiation by Free Turbulent Diffusion Flames', *Combustion and Flame*, 1981.

Bjorge, T., and Bratseth, A. (1995). 'Measurement of Radiation Heat Flux from Large Scale Flares', *Journal of Hazardous Materials*, Volume 46, p159-168.

Briggs, G. A. (1969). Plume Rise. TID 25075 Clearinghouse for Federal Scientific and Technical Information, Springfield, Va.

Brzustowski, T. A. (1976). 'Flaring In The Energy Industry', *Progress in Energy and Combustion Science*, Volume 2, p129-141.

Brzustowski, T. A., Gollahalli, S. R., Gupta, M. P., Kaptein, M. and Sullivan, H. F. (1975). 'Radiant Heating From Flares', ASME paper 75-HT-4, Heat Transfer Conference, August 1975.

Brzustowski, T. A. and Sommer, E. C. Jr. (1973). 'Predicting Radiant Heating from Flares', American Petroleum Institute Proceedings, API Division of Refining, Washington, D.C., Volume 53, p865-893.

Chamberlain, G. A. (1987). 'Developments in Design Methods for Predicting Thermal Radiation from Flares', *Chemical Engineering, Research and Design*, Volume 65, July 1987.

Cook, D. K., Fairweather, M., Hammonds, J. and Hughes, D. J. (1987a) 'Size and Radiative Characteristics of Natural Gas Flares. Part 1 – Field Scale Experiments', *Chemical Engineering, Research and Design*, Volume 65, July 1987, 318-325.

Cook, D. K., Fairweather, M., Hammonds, J. and Hughes, D. J. (1987b) 'Size and Radiative Characteristics of Natural Gas Flares. Part 2 – Empirical Model', *Chemical Engineering, Research and Design*, Volume 65, July 1987, p310-317.

Chapra, S. C. (1997). Surface Water-Quality Modeling, McGraw-Hill Series in Water Resources and Environmental Engineering.

Davies, M. J. E. and Leahey, D. M. (1981). 'Field Study of Plume Rise and Thermal Radiation from Sour Gas Flares', Alberta Environment and Alberta Energy Resources Conservation Board, 1101/160/mac, June 1981.

De-Faveri, D. M., Fumarola, G., Zonato, C. and Ferraiolo, G. (1985). 'Estimate Flare Radiation Intensity', *Hydrocarbon Processing*, Volume 64, Number 5, May 1985, p89-91.

Dubnowski, J. J. and Davies, B. C. (1983). 'Flaring Combustion Efficiency: A Review of the State of Current Knowledge', Proceedings of the Annual Meeting Air Pollution Control Association, Atlanta, Georgia, 76th, Volume 4, Published by APCA, Pittsburgh, Pa, USA 83-52. 10, 27p

Durst, F., Melling, A. and Whitelaw, J. H. (1976). Principles and Practice of Laser-Doppler Anemometry, Academic Press.

Evans, F. L. Jr. (1980). Equipment Design Handbook for Refineries and Chemical Plant, 2nd Edition, Gulf Publishing Company, Houston, Texas, 1974.

EERC (1983). Evaluation Of The Efficiency Of Industrial flares: Background - Experimental Design - Facility. Rept. on Phase 1 and 2. Oct 80-Jan 82. Energy and Environmental Research Corporation, Irvine, California.

Fumarola, G., De-Faveri, D. M., Pastorino, R. and Ferraiolo, G. (1983). 'Determining Safety Zones for Exposure to Flare Radiation', Institution of Chemical Engineers Symposium Series, Number 82. Published by the Institute of Chemical Engineers (EFCE Publications Series n 33), Rugby, Warwickshire, England. Distributed by Pergamon Press, Oxford, Engl & New York, NY, USA pG23-G30.

Hajek, J. D. and Ludwig, E. E. (1960). 'Safe Design of Flare Stacks for Turbulent Flow', *Petroleum and Chemical Engineering Journal*, June-July C31-C38, 1960.

Johnson, A. D., Ebbinghaus, A., Imanari, T., Lennon, S. P. and Marie, N. (1997). 'Large-Scale Free and Impinging Turbulent Jet Flames: Numerical Modeling and Experiments', *Process Safety and Environmental Protection*, 75:(B3) 145-151 August 1997.

Kent, G. R. (1964). 'Practical Design of Flare Stacks', *Hydrocarbon Processing*, Volume 43, Number 8, p121-125.

Leahey, D. M., and Davies, M. J. E. (1984). 'Observations of Plume Rise from Sour Gas Flares', *Atmospheric Environment*, Volume 18, Number 5, p917-922.

Leahey, D. M. (1979). 'A Preliminary Study Into The Relationships Between Thermal Radiation And Plume Rise', Published in Edmonton: Alberta Environment, May 1979, 33 p.

Leite, O. C. (1991). 'Smokeless, Efficient, Nontoxic Flaring', Hydrocarbon Processing, Volume 70, Number 3, March 1991, p77-80.

Markstein, G. H. (1975). 'Radiative Energy Transfer from Turbulent Diffusion Flames', Technical Report, FMRC Serial Number 22361-2 Factory Mutual Research Corp, 1975. Also ASME paper 75-HT-7 (1975)

McMurray, R. (1982). 'Flare Radiation Estimated', *Hydrocarbon Processing*, November 1982, p175-181

Oenbring, P. R. and Sifferman, T. R. (1980a). 'Flare Design Based on Full-Scale Plant Data', Proceedings of the American Petroleum Institute's Refining Department, Volume 59, Midyear Meeting, 45th, Houston, Texas, May 12-15, Published by API, p220-236.

Oenbring, P. R. and Sifferman, T. R. (1980b). 'Flare Design...Are Current Methods Too Conservative?', *Hydrocarbon Processing*, Volume 59, Number 5, May 1980, p124-129.

Pavel, A. and Dascalu, C. (1990(a)). 'Thermal Design of Industrial Flares. Part 1'. *International Chemical Engineering*, Volume 30, Number 2, April 1990.

Reed, R. D. (1981). Furnace Operations, 3rd Edition, Gulf Publishing Company, Houston, Texas.

Schmidt, T. R. (1977). 'Ground-Level Detector Tames Flare-Stack Flames', *Chemical Engineering*, April 11, 1977.

Schwartz, R. E. and White, J. W. (1996). 'Flare Radiation Prediction: A Critical Review'. 30th Annual Loss Prevention Symposium of the American Institute of Chemical Engineers, February 28, 1996. Session 12: Flare Stacks and Vapor Control Systems.

Seigal, K. D. (1980). 'Degree of Conversion of Flare Gas in Refinery High Flares', Ph.D. Dissertation, University of Karlsruhe (German), February 1980.

Stone, D. K., Lynch, S. K. and Pandullo, R. F. (1992). 'Flares. Part 1: Flaring Technologies for Controlling VOC-Containing waste Streams', *Journal of the Air and Waste Management Association*, Volume 42, Number 3, March 1992, p333-340.

Strosher, M. (1996). 'Investigations of Flare Gas Emissions in Alberta', Alberta Research Council for Environment Canada Conservation and Protection and the Alberta Energy and Utilities Board, November 1996.

Strosher, M., Allan, K. C. and Kovacik, G. (1998). 'Removal of Liquid from Solution Gas Streams Directed to Flare and Development of a Method to Establish the Relationship between Liquids and Flare Combustion Efficiency'. Alberta Research Council for Alberta Environmental Protection, Edmonton, Alberta, March 1998.

Sunderland, P. B., Koylu, U. O. and Faeth, G. M. (1994). 'Soot Formation in Weakly Buoyant Acetylene-Fuelled Laminar Jet Diffusion Flames Burning in Air', Presented at the Twenty-Fifth Symposium (International) on Combustion, Irvine, California, 31 July – 5 August 1994, p310-322.

Tan, S. H. (1967). 'Flare System Design Simplified', *Hydrocarbon Processing*, Volume 46, Number 1, January 1967, p172-176.

Zabetakis, M. G. and Burgess, D. S. (1961). 'Research on the Hazards Associated with the Production and Handling of Liquid Hydrogen', R.I. 5707, U.S. Bureau of Mines, 1961.

Appendix 1

Values for the Fraction of Heat Radiated Values given in the Literature

Appendix 1 – Fraction of Heat Radiated Values given in the Literature

Citation		Value of fraction of heat radiated	Notes
Zabetakis and Burgess	1961	0.17	Hydrogen, max. value
Zabetakis and Burgess	1961	0.38	Ethylene, max. value
Zabetakis and Burgess	1961	0.16	Methane, max. value
Zabetakis and Burgess	1961	0.30	Butane, max. value
Zabetakis and Burgess	1961	0.23	Natural gas, max. value
Tan	1967	0.2	Methane
Tan	1967	0.33	Propane
Tan	1967	0.4	Higher molecular weight hydrocarbons
API RP 521	1969	0.16	Methane, max. value in still air
API RP 521	1969	0.20	Methane
API RP 521	1969	0.30	Heavier gases than methane
Brzustowski et al.	1975	0.155	Methane, gas exit vel. = 30.9m/s, still air
Brzustowski et al.	1975	0.17	Methane, gas exit vel. = 24.5m/s, still air
Brzustowski et al.	1975	0.23	Methane, gas exit vel. = 30.9m/s, cross-wind 2m/s
Brzustowski et al.	1975	0.26	Methane, gas exit vel. = 24.5m/s, cross-wind 2m/s
Markstein	1975	0.204 – 0.246	Propane, still air, jet nozzles increasing in diameter
Markstein	1975	0.17 – 0.18	Propane, still air, gas exit vel. = 2 orders of magnitude higher than above tests
Leahey et al.	1979	0.28	Max. value, 4 – 40% H_2S
Oenbring	1980	0.50	Heavy gases, calculated value, assumes flared products 100% combusted
Oenbring	1980	0.25	Gas = 16.8 M.W.
Oenbring	1980	0.40	Gas = 40 M.W. with steam
Oenbring	1980	0.50	Gas = 40 M.W. without steam
McMurray	1982	0.207	Gas = 41 M.W., flame length = 115 ft., Q = 1.34×10^9 Btu/hr, steam assisted, calc. from API model
McMurray	1982	0.224	Gas = 41 M.W., flame length = 115 ft., Q = 1.34×10^9 Btu/hr, steam assisted, calc. from IMS model
Fumarola et al.	1983	0.3	Methane and LPG, flow rate = 200 000kg/hr
Leahey and Davies	1984	0.55	Validated experimentally, H_2S present at 0.2 – 1%
De-Faveri et al.	1985	0.3	Value quoted and used in all calculations
Cook et al.	1987	$=0.321 - 0.418\times10^{-3}u_j$	u_j = gas velocity, derived empirically
Chamberlain	1987	$=0.21e^{-0.00323u_j} + 0.11$	U_j = gas velocity, derived empirically
Leite	1991	0.15	Gas mixture, air assisted, air stream vel. 120 ft/sec
Leite	1991	0.15	Hydrogen
Sunderland et al.	1994	0.29 – 0.34	Lab-scale tests, 5cm flame length, C_2H_2/N mixture

Appendix 2

Literature Listing

1 Observations of plume rise from sour gas flares

1.1 Leahey-D-M; Davies-M-J-E

SO: Atmos-Environ. v 18 n 5 1984, p 917-922

ST: Atmospheric-Environment

IS: 0004-6981

AB: The rise of a plume resulting from the operating of a flare was evaluated in winter and summer during neutral and unstable atmospheric conditions. The plume was made visible through the injection of oil into the flame. Analysis of wind information, plume photographs, and infrared thermometer data showed that: the plume behaved in a manner that would have been predicted on the basis of the 2/3 plume rise formula; the amount of entrainment of air into the flare plume was similar to that found by other investigators for a conventional stack plume; about 55 percent of the heat of combustion of flared gases was lost due to radiation; the value of the coefficient, C sub 1, used in the 2/3 plume rise formula should be 1. 64 and the correlation coefficient between 777 observed and theoretical plume rises was 0. 74. Refs.

MH: PETROLEUM-REFINERIES

DE: ATMOSPHERIC-MOVEMENTS-Monitoring; GAS-DYNAMICS-Evaluation

FL: PLUME-BEHAVIOR-RESEARCH

CC: 513 (Petroleum-Refining); 402 (Buildings-and-Towers); 443 (Meteorology); 931 (Applied-Physics-Generally)

PY: 1984

LA: English

UD: 8409

2 A theoretical assessment of flare efficiencies as a function of gas exit velocity and wind speed

2.1 Leahey D M, Schroeder M B, Hansen M C

ENVIRON SERV ASS ALBERTA ET AL FLARING TECHNOLOGY SYMPOSIUM (EDMONTON, CAN, 2/21/96)

PROC 1996 (15 PP; 22 REFS)

Complete combustion is usually the goal of hydrocarbon burning processes utilized for industrial purposes. Achievement of complete combustion is associated with maximum heat release, calculated on the assumption that all hydrocarbons are chemically converted to carbon dioxide (CO2) and water (H2O). Flaring of gases in the free atmosphere is a process routinely used in the petroleum and chemical industry for the disposal of unwanted flammable gases and vapors. It is, however, rarely successful in the attainment of complete combustion, because entrainment of air into the region of combusting gases restricts flame sizes to less than optimum values. These restrictions occur because the entrained air reduces hydrocarbon concentrations below values needed to support combustion. Equations that incorporate entrainment effects have been previously developed by Leahey and Schroeder (1987) for estimating flame dimensions as functions of gas exit velocity, stoichiometric mixing ratios, and wind speed. These equations are used to estimate the rate of sensible heat exchange and heat radiation associated with flame behavior for different hydrocarbons and a variety of conditions related to exit gas velocity and wind speeds. Results of the calculations show that heat releases are usually much less than those that should accompany

complete combustion. They imply that actual flaring activities result in combustion efficiencies that are routinely less than 50%.

3 Estimate flare radiation intensity

3.1 De-Faveri D M, Fumarola G, Zonato C; Ferraiolo G

SO: Hydrocarbon-Processing. v 64 n 5 May 1985, p 89-91

ST: Hydrocarbon-Processing

IS: 0018-8190

AB: Thermal radiation intensity from flares is more accurately determined when the flame source is considered as a surface. Normal procedure has been to evaluate radiation intensity assuming a point source at various locations or as a uniform distribution along the flame axis. Thermal radiation from heat release by combustion depends on chemical composition of the waste gas burned, since radiant energy originates basically from carbon dioxide, water vapor and solid carbon particles. Prediction of jet diffusion flame shape and size in crosswind is of practical interest to assess radiative heat flux to neighboring plant structures or operating personnel. In fact, this is the basis for evaluating required safety distances (height of the flare stack) or choice of safety devices (sprinklers, water curtains).

MH: PETROLEUM-REFINERIES-Flare-Stacks

DE: HEAT-TRANSFER-Radiation; MATHEMATICAL-TECHNIQUES

FL: FLARE-RADIATION-INTENSITY; FLAME-SHAPE-AND-SIZE; THERMAL-RADIATION

CC: 513 (Petroleum-Refining); 402 (Buildings-and-Towers); 641 (Heat-and-Mass-Transfer,-Thermodynamics); 601 (Mechanical-Design); 802 (Chemical-Apparatus-and-Plants,-Unit-Operations,-Unit-Processes); 921 (Applied-Mathematics)

PY: 1985

LA: English

DT: JA (Journal-Article)

UD: 8511

4 Developments in design methods for predicting thermal radiation from flares

4.1 Chamberlain G A

SHELL RESEARCH LTD

CHEM ENG RES DESIGN, TRANS INST CHEM ENG V 65, NO 4, PP 299-309, JULY

1987 (ISSN 02638762; 8 REFS)

Models for the prediction of flame shape and radiation field are presented. These models have been extensively validated with wind tunnel experiments and field trials both on and off shore. The size of the flare boom or tower on offshore installations is often governed by peak thermal radiation exposure to personnel that would occur during emergency depressuring. This paper describes a model, which represents the flame as a frustum of a cone, radiating as a solid body with uniform surface emissive power. Correlations describing the variation of flame shape and surface emissive power under a wide range of ambient and flow conditions are discussed. It is shown that by increasing the gas exit velocity the fraction of heat released as radiation and the levels of received radiation are reduced. Correlation's of laboratory data and experience in the field have shown that

flames are fully stable under a much wider range of ambient and flow conditions than indicated in API RP 521.

5 Thermal design of industrial flares. Part I.
5.1 Pavel A, Dascalu C
SO: Int-Chem-Eng. v 30 n 2 Apr 1990, p 343-352
ST: International-Chemical-Engineering
IS: 0020-6318
AB: Using the analytic methods of S. Leichsenring and G.R. Kent, the thermal effects of industrial flares are quantified and the relevant algorithm is worked out for their thermal design. The thermal effects and implications of industrial flares are discussed independently and comparatively by three methods: The analytical method of Leichsenring, which is based on the heat of combustion of the gases burned in the flare; (2) the analytical method of G.R. Kent which based on the Stefan-Boltzmann law of thermal radiation; and (3) the graphical-analytical method of S.H. Tan which has a hybrid basis. (Edited author abstract) 27 Refs.
MH: CHEMICAL-PLANTS
DE: PETROLEUM-REFINERIES-Flare-Stacks; COMPUTER-PROGRAMMING-Algorithms
FL: INDUSTRIAL-FLARES; HEAT-FLUX-DENSITY; STEFAN-BOLTZMANN-LAW; SMOKING-FLARES; SMOKELESS-FLARES
CC: 802 (Chemical-Apparatus-and-Plants,-Unit-Operations,-Unit-Processes); 723 (Computer-Software,-Data-Handling-and-Applications); 513 (Petroleum-Refining)
PY: 1990
LA: English
DT: JA (Journal-Article)
UD: 9007

6 Thermal design of industrial flares. Part II.
6.1 Pavel A, Dascalu C
SO: Int-Chem-Eng. v 30 n 2 Apr 1990, p 353-364
IS: 0020-6318
PY: 1990
LA: English

7 Thermal design of industrial flares. Part III.
7.1 Pavel A, Dascalu C
SO: Int-Chem-Eng. v 30 n 3 Jul 1990, p 535-546
IS: 0020-6318
PY: 1990
LA: English

8 Review and assessment of current flaring technology
AS: prepared by SKM Consulting Ltd. ; prepared for Environmental Protection Service, Western and Northern Region in association with Government Industry Consultative Committee on Flaring

CS: SKM-Consulting-Ltd; Government-Industry-Consultative-Committee-on-Flaring; Canada-Environmental-Protection-Service-Western-and-Northern-Region
SE: Report
SD: Report / Canada. Environmental Protection Service. Western and Northern Region;CPEPWNR-87/88-5
SO: Edmonton: Environment Canada, Conservation and Protection, Environmental Protection Service, Western and Northern Region, 1988. 180 p. Bibliography; Illustrations
PY: 1988
MN: 88-03012
NF: 2 fiche
AN: 0104209
AB: Flaring has been and remains the traditional means used to dispose of industrial relief gases, which comprise a complete range of hydrocarbons, sulfur compounds, and chemical releases. In 1986, a Government Industry Consultative Committee on Flaring was established to assess flaring technology, operating practices and existing information on flare combustion. This report presents the results of Part A of the two-part study and includes a literature review and a supplier survey, as well as a review of regulatory practices in Alberta and the United States. Capital and operating costs are given, along with a comparative technical and economic assessment.
DE: Flare-gas-systems
CL: Federal; Environment; Physical-Sciences; Science; Federal; Environnement; Sciences; Sciences-physiques
NT: This work was supported by the Federal Panel on Energy R & D
LA: English
PT: Monograph; Monographie
UD: 951000

9 Improve flare design
9.1 Straitz J F
SO: Hydrocarbon-Processing. v 73 n 10 Oct 1994, 5p
ST: Hydrocarbon-Processing
IS: 0018-8190
AB: Using new safety guidelines, flaring systems can be redesigned to alleviate operating problems, meet emission-performance criteria and maintain a good-neighbor status with adjacent communities. Unfortunately, due to their high visibility, flares are easily targeted for nonperformance. Common problems are considered, including objectionable visibility, thermal radiation, smoke, odor, and noise. 10 Refs.
MH: Flare-stacks
DE: Gas-burners; Petroleum-refineries; Accident-prevention; Industrial-emissions; Smoke-abatement; Noise-abatement; Odor-control
FL: Emergency-relief-systems; Flaring-systems; Flare-visibility; Thermal-radiation
CC: 513.2 (Petroleum-Refineries); 522 (Gas-Fuels); 521.1 (Fuel-Combustion); 914.1 (Accidents-and-Accident-Prevention); 451.2 (Air-Pollution-Control)
PY: 1994
LA: English

DT: JA (Journal-Article)
UD: 9530

10 Flare technology safety
10.1 Straitz J F
SO: Chem-Eng-Prog. v 83 n 7 Jul 1987, p 53-62
ST: Chemical-Engineering-Progress
IS: 0009-2495
AB: Following a definition of a flare and the reasons for its use, the author examines the requirements of various applications. These include ammonia terminals and chemical plants; coal gasification and gas plants; offshore applications; railroad car cleaning. The use of flares in refineries and steel plants is also examined.
MH: CHEMICAL-PLANTS
DE: GASES-Combustion; PETROLEUM-REFINERIES-Flare-Stacks; COMBUSTION-
FL: STEAM-FLARE; FLARE-PILOTS; SMOKELESS-FLARING; THERMAL-RADIATION; FLAME-STABILITY
CC: 802 (Chemical-Apparatus-and-Plants,-Unit-Operations,-Unit-Processes); 914 (Safety-Engineering); 931 (Applied-Physics-Generally); 521 (Fuel-Combustion-and-Flame-Research); 513 (Petroleum-Refining); 402 (Buildings-and-Towers)
PY: 1987
LA: English
DT: JA (Journal-Article)
UD: 8804

11 Improve flare safety to meet ISO-9000 standards
11.1 Straitz-JF III
SO: Hydrocarbon-Processing. v 75 n 6 Jun 1996, 4pp
IS: 0018-8190
PY: 1996
LA: English

12 Flaring for Safety and Environmental Protection.
12.1 Straitz, John F.
APPEARS IN: Drilling-DCW Nov 1977, v.39, no.1, p.45 (4 p.)
PUBLISHED: Nov 1977 19771100
PAGING: 1 diagram, 5 photos, 3 references
SUMMARY: Flares are emergency burners for safe disposal of hydrocarbon gases and vapors during drilling, production, transportation, refining, chemical processing, and distribution. Vital to personnel and equipment safety, they must also be designed to protect the environment from unburned hydrocarbons. Factors influencing safe and environmentally acceptable flare design are: sizing and pressure drop; thermal radiation; liquid carry-over; smokeless operation/complete combustion; and reliable pilot and ignition. Each of these characteristics is detailed.
SUBJECTS: THERMAL RADIATION, COMBUSTION, SMOKE, and FLARE GAS
Research article OCLC #: ena78210830

13 Make the flare protect the environment.
13.1 Straitz, John F.
APPEARS IN: Hydrocarbon Processing, Oct 1977, v.56, no.10, p.131 (5 p.)
PUBLISHED: Oct 1977 19771000
PAGING: 2 diagrams, 3 photos, 13 references
SUMMARY: Properly designed and operated flares protect the environment while being used to eliminate gaseous waste streams safely and economically. Designs must be made with great care, and flare application must be knowledgeable engineered to assure optimal performance. Thermal radiation, liquid carryover, and explosion hazard resulting from air entry into the stack are important design factors to be considered. Operational considerations include such factors as: stable and complete combustion; noise; positive piloting; reliable ignition; effective steam or assist gas control; and smokeless operation. Ammonia, air blower, and multiple high velocity flares are examined. Some BASIC rules to be observed to assure proper flare mechanical design are: no moving parts; no burning inside the flare tip; and no small openings for steam or gas injectors.
SUBJECTS: MATHEMATIC MODELS, AIR TEMPERATURE, INCINERATION, NOISE POLLUTION CONTROL, FLARE GAS, STACK EMISSION CONTROL
Research article OCLC #: eva78021100

14 Sizing process flares: nomogram determines proper flare-stack height
14.1 STRAITZ J F III
OIL GAS PETROCHEM EQUIP V 25, NO 10, P 25, AUG 1979 (ISSN 00301353)
LANGUAGE: ENGLISH
Large volumes of flammable, toxic, or corrosive vapors are converted to less objectionable compounds by elevated process flares. These flares are elevated to reduce thermal radiation at grade or base level and to minimize adverse effects of flame length and wind tilt. In sizing an elevated flare, the first step is to determine the proper flare-tip diameter. A new nomogram is provided to estimate overall flare-stack height. All important factors have been taken into consideration, within scale limits, to insure acceptable radiation levels for personnel and equipment within a plant or refinery. A sample problem and solution are presented.

15 Smokeless, efficient, nontoxic flaring
15.1 Leite O C
SO: Hydrocarbon-Processing. v 70 n 3 Mar 1991, p 77-80
ST: Hydrocarbon-Processing
IS: 0018-8190
AB: The primary function of a flare is to dispose of toxic, corrosive or flammable vapors safely, under relief conditions, by converting them into less objectionable products by combustion. Either elevated flares or ground flares can accomplish efficiently the discharges to atmosphere when properly designed. Proper design is based on the characteristics of waste gas, heat radiation, noise levels, smoke and atmospheric dispersion. 14 Refs.
MH: Flare-Stacks
DE: Environmental-Protection; Efficiency-; Combustion-;Hydrocarbons-; Environmental - engineering

FL: Smokeless-Flaring; Hydrocarbon-Discharge; Automatic-Smoke-Control
CC: 513.2 (Petroleum-Refineries); 454.2 (Environmental-Impact-and-Protection); 521 (Fuel-Combustion-and-Flame-Research); 804 (Chemicals-Generally)
PY: 1991
LA: English
DT: JA (Journal-Article)
UD: 9325

16 Predictions of radiative transfer from a turbulent reacting jet in a cross-wind
16.1 Fairweather M, Jones W P; Lindstedt R P
SO: Combust-Flame. v 89 n 1 Apr 1992, p 45-63
ST: Combustion-and-Flame
IS: 0010-2180
AB: Predictions of the structure and received thermal radiation around a turbulent reacting jet discharging into a cross-flow have been made using a finite-difference scheme for solving the fluid dynamic equations. The model employs a two-equation, k-epsilon turbulence model. The gas-phase, non-premixed combustion process is modeled via the conserved scalar/prescribed probability density function approach using the laminar flamelet concept, whilst soot formation and consumption is included through balance equations for mass fraction and particle number density which admit finite-rate kinetic effects. Both flamelet and sooting prescriptions are derived from a global reaction scheme for hydrocarbon combustion. Levels of radiation received around a flame are obtained using the discrete transfer method coupled to a narrow band model of radiative transfer. In order to assess the usefulness of the model for predicting the consequences associated with atmospheric venting and flaring operations, solutions are compared with experimental data from laboratory and field scale studies of natural gas flames. Predictions are shown to be in good agreement with measurements of received radiation made around all the flames examined. In particular, results for a number of sooting strain rates indicate that a single rate suffices for predicting the radiation received about a wide range of flame sizes. (Author abstract) 43 Refs.
MH: JETS-
DE: HEAT-TRANSFER; HEAT-RADIATION; MATHEMATICAL-MODELS; COMBUSTION-; FINITE-DIFFERENCE-METHOD; WIND-EFFECTS
FL: RADIATIVE-TRANSFER; TURBULENT-REACTING-JET; CROSS-WIND; ATMOSPHERIC-VENTING; FLARING-; SOOTING-STRAIN-RATE
CC: 631 (Fluid-Flow); 641 (Heat-and-Mass-Transfer,-Thermodynamics); 521 (Fuel-Combustion-and-Flame-Research); 921 (Applied-Mathematics)
PY: 1992
LA: English
DT: JA (Journal-Article)
UD: 9305

17 Upstream petroleum industry flaring guide
17.1 Alberta-Energy-and-Utilities-Board
SD: Guide series / Alberta Energy & Utilities Board ; 60

SO: Calgary, AB: Alberta Energy & Utilities Board, 1999. v, 75 p. Illustrations; Bibliography
AB: This guide introduces a flare management framework for the Alberta upstream petroleum and gas sector. The framework includes a requirement to eliminate or reduce solution gas flare volumes and to implement new performance requirements for all flares. The guide includes information on: a decision process to be used in all solution gas conservation projects that may involve existing or new flares; flare facilities approvals; flaring at conservation facilities; clustering of several flares to a common point for conservation; royalty treatment; data requirements for reporting; well test flaring; gas battery and gas plant flaring; pipeline emissions; flare combustion efficiency standards, flare stack design and operation, and dispersion modeling requirements; gas venting; sulphur recovery requirements; flared gas measurement and reporting; industry performance reporting; and regulatory enforcement. Includes glossary.
DE: Flare-gas-systems; Petroleum-industry-and-trade,-Waste-disposal
CL: Environment; Alberta; Science; Energy; Provincial; Environment; Alberta
UD: 19991200
Published: Calgary : Alberta Energy and Utilities Board, 1999.
Waste gases --Alberta --Combustion.
Running title: EUB guide 60 : upstream petroleum industry flaring requirements
Upstream petroleum industry flaring requirements.
Material: v, 75 p. ; 28 cm.

18 Offshore stack-enclosed gas flares. Part I. Theoretical development.
18.1 Singhal SN, Delichatsois M A, de-Ris J
SO: Fire-Saf-J. v 15 n 3 1989, p 211-225
ST: Fire-Safety-Journal
IS: 0379-7112
AB: Some offshore oil production vessels are equipped with stack-enclosed gas flares. Excessive heat radiation due to flaring of produced gas can cause problems for the equipment and the crew onboard the vessel. The heat radiation from the stack depends upon many physical phenomena which cut across disciplines in thermodynamics, combustion, heat transfer, and fluid mechanics. This paper presents analyses of many different aspects of the flaring process which determine the amount of heat radiation incident on a target some distance away.
(Author abstract) 14 Refs.
MH: HEAT-TRANSFER
DE: GASES-Combustion; THERMODYNAMICS-; SHIPS-; OIL-FIELDS-Offshore
FL: STACK-ENCLOSED-GAS-FLARES; GAS-ENTHALPY; AIR-ENTRAINMENT; OFFSHORE-VESSELS
CC: 641 (Heat-and-Mass-Transfer,-Thermodynamics); 931 (Applied-Physics-Generally); 521 (Fuel-Combustion-and-Flame-Research); 671 (Naval-Architecture); 512 (Petroleum-and-Related-Deposits)
PY: 1989
LA: English
DT: JA (Journal-Article)
UD: 9004

19 Offshore stack-enclosed gas flares. Part II. Application and results.

19.1 Singhal S N, Delichatsios M A, de-Ris J

SO: Fire-Saf-J. v 15 n 3 1989, p 227-244

ST: Fire-Safety-Journal

IS: 0379-7112

AB: This paper presents results for the heat radiated from the hot gas plume to personnel on the deck of the vessel. A sensitivity study for the effect of relevant system parameters on heat radiation level shows that the most important effect is due to the product of the flow rate and the heating value of the gas. Three case studies were conducted for low, medium, and high capacity flares. Results are discussed with respect to limiting flare capacities. The calculated heat radiation levels were compared with allowable limits for continuous human exposure specified by the American Bureau of Shipping (ABS). The maximum heat

radiation levels from the flare systems of the low and medium capacity cases were found to be well below the allowable limits. (Edited author abstract) 2 Refs.

MH: HEAT-TRANSFER

DE: gases, mathematical techniques, Sensitivity-Analysis, THERMODYNAMICS, OIL-FIELDS; SHIPS-

FL: STACK-ENCLOSED-GAS-FLARES; GAS-PLUMES; GAS-FLOW-RATES; OFFSHORE-VESSELS

CC: 641 (Heat-and-Mass-Transfer,-Thermodynamics); 521 (Fuel-Combustion-and-Flame-Research); 931 (Applied-Physics-Generally); 671 (Naval-Architecture); 921 (Applied-Mathematics); 512 (Petroleum-and-Related-Deposits)

PY: 1989

LA: English

DT: JA (Journal-Article)

UD: 9004

20 Aplicacion del metodo Brzustowski para el dimensionamiento de quemadores elevados.

20.1 Application of the Brzustowski method for elevated flare design.

AU: Garcia-Nava-Rafael; Ochoa-De-la-Torre-Carlos

SO: Rev-Inst-Mex-Pet. v 21 n 32 Apr-Jun 1989, p 48-56

ST: Revista-del-Instituto-Mexicano-del-Petroleo

IS: 0538-1428

AB: According to the actual environmental regulations on emission and production of noise, smoke and thermal radiation, the design of flare systems has increased in importance. Actually, an emergency relief in a process plant can produce a large flame of several hundred feet length, with a significant quantity of

energy irradiated to the surroundings. This situation is particularly critical in the case of offshore platforms, where the flare is an important part of the process because economics often prohibit locating it sufficiently far away that it has no impact on personnel or equipment. The purpose of this paper is to present a computer program calculation of the more important factors in the elevated flare design by means of the Brzustowski method. (Edited author abstract) 10 Refs. In Spanish.

MH: PETROLEUM-REFINERIES

DE: OFFSHORE-STRUCTURES-Flare-Stacks; PRODUCTION-PLATFORMS-Flare-Stacks; COMPUTER-SOFTWARE
FL: BRZUSTOWSKI-METHOD; ELEVATED-FLARE-DESIGN
CC: 513 (Petroleum-Refining); 674 (Small-Craft-and-Other-Marine-Craft); 512 (Petroleum-and-Related-Deposits); 723 (Computer-Software,-Data-Handling-and-Applications)
PY: 1989
LA: Spanish
DT: JA (Journal-Article)
UD: 9003

21 Size and radiative characteristics of flares. Part 1 – field scale experiments
21.1 Cook-D-K; Fairweather-M; Hammonds-J; Hughes-D-J
SO: Chem-Eng-Res-Des. v 65 n 4 Jul 1987, p 310-317
ST: Chemical-Engineering-Research-and-Design
IS: 0263-8762
AB: In this, the first part of a two part study of flares, data obtained from fifty seven field scale experiments is described. The flares employed were of natural gas, with both subsonic and sonic releases having been considered. Experimental data on the size, shape and radiative characteristics of the flares has been obtained, in addition to measurements of thermal radiation incident about the flares. This data has been compared with results obtained from prediction methods described in published recommendations for the design of flaring systems. Comparison of flame length and trajectory reveal significant differences between theory and experiment although, on average, recommendations for the fraction of heat radiated from a flare are in reasonable agreement with experimental data. In agreement with previous findings, results for the levels of thermal radiation encountered in the near field of a flare obtained from the recommended prediction methods were found to severely ov erestimate experimental data. (Author abstract) 22 refs.
MH: NATURAL-GAS-WELLS
DE: FLAME-RESEARCH; HEAT-TRANSFER-Radiation
FL: NATURAL-GAS-FLARES; FLARE-SIZE; RADIATIVE-CHARACTERISTICS
CC: 512 (Petroleum-and-Related-Deposits); 521 (Fuel-Combustion-and-Flame-Research); 641
(Heat-and-Mass-Transfer,-Thermodynamics)
PY: 1987
LA: English
DT: JA (Journal-Article)
UD: 8712

22 Size and radiative characteristics of flares. Part 2 – empirical model.
22.1 Cook-D-K; Fairweather-M; Hammonds-J; Hughes-D-J
SO: Chem-Eng-Res-Des. v 65 n 4 Jul 1987, p 318-325
ST: Chemical-Engineering-Research-and-Design
IS: 0263-8762

AB: A study of flares is completed with the presentation of a mathematical model for the prediction of incident thermal radiation. The model is based on the experimental data obtained in fifty seven field scale experiments described in the first part of the study. This data has been incorporated into a single algorithm for the prediction of flame length and the trajectory of the flame locus, and has been used to define the radiative characteristics of a flare. The flare as an emitter of thermal radiation has been represented within the model by a series of point source emitters, uniformly distributed along the flame locus. Experimentally observed variations in the radiative power of a flare along its locus were then represented by weighting the power of the point sources to a sine squared function. Predictions of the model are in satisfactory agreement with measurements of incident thermal radiation. The complete model provides a relatively simple method for the rapid computation of thermal radiation incident at any position around a flare resulting from subsonic and sonic releases of natural gas into a wind-blown environment. (Author abstract) 17 refs.
MH: NATURAL-GAS-WELLS
DE: FLAME-RESEARCH-Mathematical-Models; HEAT-TRANSFER-Radiation FL: NATURAL-GAS-FLARES; FLARE-SIZE; RADIATIVE-CHARACTERISTICS
CC: 512 (Petroleum-and-Related-Deposits); 521 (Fuel-Combustion-and-Flame-Research); 921 (Applied-Mathematics); 641 (Heat-and-Mass-Transfer,-Thermodynamics)
PY: 1987
LA: English
DT: JA (Journal-Article)
UD: 8712

23 Stack sizing calculations can be programmed on a microcomputer
23.1 Tsai-Tom-C
SO: Oil-Gas-J. v 84 n 43 Oct 27 1986, p 82-85
ST: Oil-and-Gas-Journal
IS: 0030-1388
AB: The industrial standard practice of flare-stack sizing follows the procedures outlined in the American Petroleum Institute (API) standard RP-521. Recently, an alternate procedure has been proposed by others. This new procedure incorporates a new prediction model of flame shapes and flame lengths. Both the API standard and the new procedure can be programmed for solution on a microcomputer. A comparison of the two methods is made by presenting the results of their use along with the results of other methods available in the literature. And experimental data of flame length vs. heat release is correlated. 4 refs.
MH: PETROLEUM-REFINERIES
DE: COMPUTERS,-MICROCOMPUTER; COMPUTER-PROGRAMMING-Algorithms;
MATHEMATICAL-MODELS
FL: API-STANDARD-RP-521
CC: 513 (Petroleum-Refining); 402 (Buildings-and-Towers); 722 (Computer-Hardware); 723 (Computer-Software,-Data-Handling-and-Applications); 921 (Applied-Mathematics)
PY: 1986

LA: English
DT: JA (Journal-Article)
UD: 8701

24 Offshore flare design to save weight
24.1 Barnwell-J; Marshall-B-K
SO: Annual-Meeting-American-Institute-of-Chemical-Engineers. 1984. AIChE, New York, NY, USA. 24p 2B,
CF: 1984 Annual Meeting - American Institute of Chemical Engineers. San Francisco, CA, USA
CN: 06316
SP: AIChE, New York, NY, USA
ST: Annual-Meeting-American-Institute-of-Chemical-Engineers
IS: 0196-7282
AB: Offshore platform layout is dependent upon the flare system design and its required maximum relief load. The amount of heat radiation to which equipment is exposed must be kept below defined tolerance limits. The prediction methods available for establishing heat radiation levels are compared. Various techniques for reducing flare loads and minimizing flare system cost including options in the choice of flare tip type are described. For the detailed design, liquid knock-out drums and flare tip replacement are identified as areas where savings in weight and required space are possible. BOBR.
MH: PETROLEUM-REFINERIES-Flare-Stacks
DE: OFFSHORE-STRUCTURES-Design; OIL-WELL-PRODUCTION-Offshore; NATURAL-GAS-WELLS-Offshore
FL: OFFSHORE-PLATFORMS; HEAT-RADIATION; FLARE-TIP
CC: 402 (Buildings-and-Towers); 513 (Petroleum-Refining); 674 (Small-Craft-and-Other-Marine-Craft); 511 (Oil-Field-Equipment-and-Production-Operations); 512 (Petroleum-and-Related-Deposits)
PY: 1984
LA: English
DT: CA (Conference-Article)
UD: 8504

25 Determining safety zones for exposure to flare radiation
25.1 Fumarola-G; de-Faveri-D-M; Pastorino-R; Ferraiolo-G
SO: Institution-of-Chemical-Engineers-Symposium-Series. n 82. Publ by Inst of Chemical Engineers (EFCE Publ Series n 33), Rugby, Warwickshire, Engl. Distributed by Pergamon Press, Oxford, Engl & New York, NY, USA p G23-G30
CF: 4th International Symposium on Loss Prevention and Safety Promotion in the Process Industries (EFCE Event n 290). Volume 3: Chemical Process Hazards. Harrogate, North Yorks, Engl
CN: 05523
SP: Inst of Chemical Engineers, Rugby, Warwickshire, Engl European Federation of Chemical Engineering.
ST: Institution-of-Chemical-Engineers-Symposium-Series
IS: 0307-0492

IB: 0080302939
MH: AIR-POLLUTION
FL: FLARE-RADIATION; FLAME-RADIATION-EXPOSURE-SAFETY-ZONES; FLARE-STACK-DESIGN; TURBULENT-HYDROCARBON-JETS-DISPERSION; THERMAL-RADIATION; FLAME-SHAPE; FLAME-LENGTH; COMBUSTION-EQUIPMENT; TOXIC-MATERIALS-CONVERSION; POLLUTING-SUBSTANCES-CONVERSION; HAZARDOUS-MATERIALS-COMBUSTION
CC: 451 (Air-Pollution); 914 (Safety-Engineering); 521 (Fuel-Combustion-and-Flame-Research)
PY: 1983
LA: English
DT: CA (Conference-Paper)-
UD: 8412

26 Estimation of available flare capacity
26.1 Ortner P
SO: v 2. Available from Technical Univ of Graz, Graz, Austria p 499-509
CF: Proceedings of the 3rd Austrian - Italian - Yugoslav Chemical Engineering Conference. 276th Event of the European Federation of Chemical Engineering. Graz, Austria
CN: 03642
SP: Technical Univ of Graz, Inst of Chemical Engineering, Graz, Austria Austrian Assoc of Chemical Apparatus Construction & Chemical Engineering, Austria
MH: PETROLEUM-REFINERIES
FL: CALCULATION-MODEL; REFINERY-BREAKDOWN; LARGE-SCALE-TEST; SCHWECHAT-REFINERY; STACK-HEAD-VELOCITY; FLARE-FIELD-HEAT-RADIATION; TEST- PERFORMANCE
CC: 513 (Petroleum-Refining); 402 (Buildings-and-Towers)
PY: 1982
LA: English
DT: CA (Conference-Paper)-
UD: 8404

27 Determine plume rise for elevated flares
27.1 Fumarola-G; DeFaveri-D-M; Palazzi-E; Ferraiolo-G
SO: Hydrocarbon-Process. v 61 n 1 Jan 1982, p 165-166
ST: Hydrocarbon-Processing
IS: 0018-8190
AB: This paper shows how plume rise from elevated flares can be determined using a semi-empirical equation based on experimental windtunnel measurements. Results are less exact than might be expected from a strictly physical mathematical approach but may prove more realistic for practical use. The solution is more advisable for use in design than the usual empirical equations normally employed even though they lack experimental support and in spite of the fact that they often do not represent a conservative result. The discussion covers the following topics: wind tunnel experiments; critical design conditions; equation

development. 13 refs.
MH: PETROLEUM-REFINERIES
DE: CHIMNEYS-Design; MATHEMATICAL-TECHNIQUES
FL: PLUME-RISE-DETERMINATION
CC: 513 (Petroleum-Refining); 402 (Buildings-and-Towers); 601 (Mechanical-Design); 921 (Applied-Mathematics)
PY: 1982
UD: 8206

28 Flare design based on full-scale plant data
28.1 Oenbring-Patrick-R; Sifferman-Thomas-R
SO: Proc-Am-Pet-Inst-Refin-Dep. v 59, Midyear Meet, 45th, Houston, Tex, May 12-15 1980, Publ by API, Washington, DC, 1980 p 220-236
ST: Proceedings-American-Petroleum-Institute,-Refining-Department
IS: 0364-4030
AB: Thermal radiation intensity, noise, and flame length and deflection data were obtained from actual plant flares for various gas rates, wind directions, and distances from the flame. The data were evaluated in terms of API RP 521 and other flare-related literature. The data indicate that the point-source approach
to flare calculations is adequate for design, and that an F factor of 0. 25 should be used for light gases and an F factor of 0. 4 to 0. 5 should be used for heavy gases. Flame size and deflection are best predicted using the Brzustowski lean limit approach. The allowable thermal radiation heat fluxes given in API RP 521 are too conservative, and new values are suggested. 14 refs.
MH: PETROLEUM-REFINERIES
CC: 513 (Petroleum-Refining); 402 (Buildings-and-Towers)
PY: 1980
UD: 8106

29 Flare design...are current methods too conservative?
29.1 Oenbring-P-R; Sifferman-T-R
SO: Hydrocarbon-Process. v 59 n 5 May 1980, p 124-129
ST: Hydrocarbon-Processing
IS: 0018-8190
AB: Thermal radiation intensity, noise and flame length and deflection data were obtained from actual plant flares for various gas rates, wind directions and distances from the flame. The data were evaluated in terms of API RP-521 and other flare-related literature, and a revised procedure for flare design is presented. Recommended calculation procedure for flare design is included. 4 refs.
MH: PETROLEUM-REFINERIES
DE: PRODUCT-DESIGN; MATHEMATICAL-TECHNIQUES
CC: 513 (Petroleum-Refining); 402 (Buildings-and-Towers); 601 (Mechanical-Design); 921 (Applied-Mathematics)
PY: 1980
UD: 8011

30 Supersonic, high pressure, low radiation flare system design
30.1 Smith-SK; Selle-GK
SO: Offshore-Technology-Conference,-Annual-Proceedings. v 4 1997, Offshore Technol Conf, Richardson, TX, USA. 14p
CF: Proceedings of the 1997 29th Annual Offshore Technology Conference, OTC'97. Part 4 (of 4). Houston, TX, USA
IS: 0160-3663
PY: 1997
LA: English

31 Reliability-based approach reduces flare design relief load
31.1 Williams-J-Patrick; Donovan-Michael-D
SO: Oil-and-Gas-Journal. v 95 n 50 Dec 15 1997, p 47-51
IS: 0030-1388
PY: 1997
LA: English

32 Making the flare safe
Shore-D
SO: Journal-of-Loss-Prevention-in-the-Process-Industries. v 9 n 6 Nov 1996, p 363-381
IS: 0950-4230
PY: 1996
LA: English

33 Steam-assisted flare eliminates environmental concerns of smoke and noise
33.1 Selle-Gary-K
SO: Hydrocarbon-Processing. v 73 n 12 Dec 1994, 2p
IS: 0018-8190
PY: 1994
LA: English

34 Choose the right flare system design
34.1 Niemeyer-Christopher-E; Livingston-Gerald-N
SO: Chemical-Engineering-Progress. v 89 n 12 Dec 1993, p 39-44
IS: 0360-7275
PY: 1993
LA: English

35 Safety, noise, and emissions elements round out flare guidelines
35.1 Cunha-Leite-Olavo
SO: Oil-and-Gas-Journal. v 90 n 49 Dec 7 1992, p 68-74
IS: 0030-1388
PY: 1992
LA: English

36 Two-phase flow model aids flare network design.
36.1 Barua-Sanfanu; Sharma-Yugdutt; Brosius-Mark-G
SO: Oil-Gas-J. v 90 n 4 Jan 27 1992, p 90-94
IS: 0030-1388
PY: 1992
LA: English

37 Observations and predictions of jet diffusion flame behaviour
37.1 Leahey-Douglas-M; Schroeder-Michael-B
SO: Atmos-Environ. v 21 n 4 1987, p 777-784
IS: 0004-6981
PY: 1987
LA: English

38 Cantilevered flame boom – the effect of wind on flare exit angle
38.1 Magda-W; Marcinkowski-T; Mazurkiewicz-B-K
SO: Proceedings-of-the-International-Offshore-Mechanics-and-Arctic-Engineering-Symposium-6th.
v 1. Publ by ASME, New York, NY, USA p 275-279
CF: Proceedings of the Sixth (1987) International Offshore Mechanics and Arctic Engineering Symposium. Houston, TX, USA
PY: 1987
LA: English

39 U. S. EPA'S flare policy: update and review
39.1 Davis-B-C
SO: Chemical-Engineering-Progress. v 81 n 4 Apr 1985, p 7-10
IS: 0009-2495
PY: 1985
LA: English

40 Flares – an update of environmental regulatory policy
40.1 Davis-B-C
SO: American-Institute-of-Chemical-Engineers,-National-Meeting. 1984. AIChE, New York, NY, USA. 10p N 66B,
CF: American Institute of Chemical Engineers, 1984 Summer National Meeting (Preprints). Philadelphia, PA, USA
PY: 1984
LA: English

41 Flaring combustion efficiency: a review of the state of current knowledge
41.1 Dubnowski-John-J; Davis-Bruce-C
SO: Proceedings,-Annual-Meeting-Air-Pollution-Control-Association-76th. v 4.
Publ by APCA, Pittsburgh, Pa, USA 83-52. 10, 27p
CF: Proceedings 76th APCA Annual Meeting. Atlanta, Ga, USA
IS: 0099-4081

PY: 1983
LA: English

42 Flare efficiency studies
42.1 Davis-B-C
SO: Plant-Oper-Prog. v 2 n 3 Jul 1983, p 191-198
IS: 0278-4513
PY: 1983
LA: English

43 Flare efficiency study
43.1 Davis-Bruce-C
SO: American-Institute-of-Chemical-Engineers,-National-Meeting. 1983, Spring. Publ by AIChE, New York, NY, USA Pap 10c, 43p
CF: American Institute of Chemical Engineers, 1983 Spring National Meeting and Petro Expo '83 (Preprints). Houston, Tex, USA
PY: 1983
LA: English

44 Control emissions with flare efficiency
44.1 Romano-R-R
SO: Hydrocarbon-Process. v 62 n 10 Oct 1983, p 78-80
IS: 0018-8190
PY: 1983
LA: English

45 Are your flare systems adequate?
45.1 Chung-you-Wu
SO: Chem-Eng-(New-York). v 90 n 22 Oct 31 1983, p 41-44
IS: 0009-2460
PY: 1983
LA: English

46 Mixing and chemical reactions in industrial flares and their models
46.1 Brzustowski-T-A
SO: PCH-PhysicoChem-Hydrodyn. v 1 n 1 1980, , Proc of the Int PhysicoChem Hydrodyn Conf, 2nd, NASA, Washington, DC, Nov 6-8 1978 p 27-40
IS: 0191-9059
PY: 1978

47 Smokeless Flaring at High Rates
47.1 Straitz, J.F.
APPEARS IN: ASME Pet Mech Eng Symp, Philadelphia, PA
Sep 12-14, 1982, p.105 (6 p.)
PUBLISHED: Sep 12-14, 1982 19820900
PAGING: 4 diagrams, 1 graph, 8 photos, 5 references

SERIES: (Envirofiche ; no. 84-02853).
SUMMARY: Flaring has been the conventional technique of eliminating unwanted gases and vapors in the oil drilling and production industry for many years. To comply with environmental regulations, however, flaring must be smokeless and complete. Flare operating range, smoke formation, and smoke control are discussed with regard to meeting environmental regulations. Ambient air can be mixed with the flare stream to improve emissions.
SUBJECTS: SMOKE, ATMOSPHERIC TEMPERATURE, PYROLYSIS, FLARE GAS, EMISSION CONTROL PROGRAMS
Conf paper
OCLC #: eva84028530

48 Environmental Factors VS. Flare Application.
48.1 Schwartz, R.
APPEARS IN: Chem Eng Progr Sep 1977, v.73, no.9, p.41 (4 p.)
PUBLISHED: Sep 1977 19770900
PAGING: 1 diagram, 3 photos, 11 references
SERIES: (Envirofiche ; no. 78-00721).
SUMMARY: The flare system's most dramatic impact on the environment is its potential for producing very large flames and clouds of smoke. Current environmental requirements force the plant designer to route more of the vented gases into the flare system. The use of larger components in such designing has increased the amount of gas that must be handled smokelessly by the flare. The weight ratio of hydrogen to carbon is a key factor concerning smoke emission. Kinetic energy in the combustion zone is discussed as another factor.Radiation levels and smoke suppressant controls are surveyed.
SUBJECTS: SMOKE HYDROGEN CARBON CHLORINATED HYDROCARBONS, SULFUR COMPOUNDS, ALASKA, FLARE GAS
Research article
OTHER ENTRY: Keller, M. John Zink Co, Tulsa
OCLC #: eva78007210

49 Ground-Level Detector Tames Flare-Stack Flames.
49.1 Schmidt, Thomas R.
APPEARS IN: Chem Eng Apr 11, 1977, v.84, no.8, p.121 (4 p.)
PUBLISHED: Apr 11, 1977 19770400
PAGING: 3 drawings, 3 graphs, 2 photos, 8 references
SUMMARY: The Shell Oil Co. Has developed a flare control system that has proved to be substantially simpler than previous systems and more effective in promoting smokeless combustion. The concept is based on measuring the radiant-heat energy from a portion of the flame with a ground level sensor. The heart of the system is an optical monitor located at a moderate distance from the base of the flare stack and trained on the base region of the flame. The advantages of the system are: (1) relatively low, simple maintenance; (2) installation or inspection without shutdown; (3) ground level installation; (4) rapid response to burning conditions; and (5) reduction of operating costs and flare noise while providing smokeless burning. Limitations are: no provision for flare-gas flow measurement; and inability to anticipate arrival of flare gas. The design

of a flare-stack control system, the monitor designs and characteristics, the location of the monitor, and the effect of flare characteristics on radiation are detailed.
SUBJECTS: THERMAL PLUMES, AIR OPTICAL PROPERTIES , OIL REFINERY OPERATION, MATHEMATIC MODELS, RADIATION, FLARE GAS, RADIATION INSTRUMENTS
Journal article
OCLC #: eva77056180

50 Flaring in the Energy Industry.
50.1 Brzustowski, T.A.
APPEARS IN: Progr Energy Combust Sci-Pergamon 1976, v.2, no.3, p.129 (13 p.)
PUBLISHED: 1976 19760000
PAGING: 7 diagrams, 38 references, 3 tables
SUMMARY: Flaring is the combustion process used for the safe disposal of large quantities of flammable gases and vapors in the petroleum industry. A critical review of the flaring technology is presented. The length and shape of the flame on an elevated flare, its radiation field, and noise and air pollution from flares are discussed. It is likely that the elevated flare will remain the only reliable means for the safe disposal of large amounts of gases and vapors in an emergency.
SUBJECTS: STACK EMISSIONS, SMOKE, SCALING, FLARE GAS, PETROLEUM INDUSTRY
Research article
OCLC #: eva77014380

51 A Generalized Approach to Flare Gas Energy Recovery System Design.
51.1 Hardison, L.C.
APPEARS IN: Assoc of Energy Eng Energy Utilization Technol World Energy Eng 4th Symp, Atlant Oct 12-15, 1981, p.203 (6 p.)
PUBLISHED: Oct 12-15, 1981 19811000
PAGING: 1 diagram, 3 tables
SERIES: (Energyfiche ; no. 83-24916).
SUMMARY: The importance of heat and fuel gas recovery is emphasized in light of energy price increases. Recovery of the energy presently lost daily from flare systems in petroleum refineries and petrochemical plants is explained. The design and operation of a vapor recovery system is described. Flow measurement, safety, equipment requirements, and economic aspects are considered. Even for small systems recovering 500 standard Cu ft/minute of flare gas and having a capital investment of $1.2 million, sufficient energy is recovered to result in a pay out time of less than two years at current prices. Pay out times can be less than six months for larger systems.
SUBJECTS: COMPRESSOR STATIONS, PETROCHEMICAL PLANTS, OIL REFINERIES, ECONOMICS, ENERGY USAGE, INDUSTRIAL CAPITAL COSTS, OPERATING AND MAINTENANCE COSTS, CONFERENCE PAPER, HEAT RECOVERY, FLARE GAS
OTHER ENTRY: Nagl, G.J. Air Resources Inc
Pittas, J.J. Air Resources Inc
OCLC #: ena83249160

52 Evaluation of the Efficiency of Industrial Flares: Background - Experimental Design - Facility. Rept. on Phase 1 and 2. Oct 80-Jan 82.

CS: Performer: Energy and Environmental Research Corp., Irvine, CA.
Funder: Industrial Environmental Research Lab., Research Triangle Park, NC.

RD: Aug 83. 287p.

PR: PC A13/MF A01

DE: *Flares-; *Industrial-plants; *Waste-disposal; Mathematical-models; Petroleum-products; Blast-furnaces; Chemical-industry; Coking-; Soot-; Sampling-; Combustion-products; Industrial-wastes.

DE: *Flares-; *Industrial-plants; *Waste-disposal.

ID: *Pollution-control.

ID: *Pollution-control.

AB: The report summarizes the technical literature on the use of industrial flares and reviews available emission estimates. Technical critiques of past flare efficiency studies are provided. Mathematical models of flame behavior are explored and recommendations for flare flame models are made. The parameters affecting flare efficiency are evaluated, and a detailed experimental test plan is developed. The design of a flare test facility is provided, including details on the flare tips, fuel and steam supplies, flow control and measurement, emissions sampling and analysis, and data acquisition and processing.

RN: EPA600283070

Contract: EPA68023661

53 Combustion Efficiency of Flares. Rept. for Oct 80-Feb 84.

CS: Performer: Energy and Environmental Research Corp., Irvine, CA.
Funder: Environmental Protection Agency, Research Triangle Park, NC. Air and Energy Engineering Research Lab.

RD: Aug 85. 23p.

PR: PC A02/MF A01

DE: Gases-; Exhaust-gases.

DE: *Decoys-; *Combustion-efficiency; *Hydrocarbons-.

ID: *Flares-.

AB: The paper gives results of a study to provide data on industrial flare emissions. (Emissions of incompletely burned hydrocarbons from industrial flares may contribute to air pollution. Available data on flare emissions are sparse, and methods to sample operating flares are unavailable.) Tests were conducted on 3-, 6-, and 12-in. diameter flare heads. Propane was used as the flare fuel, diluted with nitrogen to control the heating value. The following results were obtained: (1) soot (from smoky flares) accounts for <0.5% of the unburned hydrocarbon emissions; (2) the size of the flare head did not influence hydrocarbon combustion efficiency; and (3) the stability of the flare flame influenced combustion efficiency, with unstable flames tending to promote inefficient combustion. A relationship between gas heating value and exit velocity was developed to denote the region of flame instability.

RN: EPA600D85188

CN: Contract: EPA68023661

54 Policy review of solution gas flaring and conservation in Alberta.
CS: Performer: Alberta Energy & Utilities Board, Calgary, (Alberta).
RD: c1997. 49p.
AV: Microfiche only. Order this product from NTIS by: phone at 1-800-553-NTIS (U.S. customers); (703)605-6000 (other countries); fax at (703)321-8547; and email at orders ntis.fedworld.gov. NTIS is located at 5285 Port Royal Road, Springfield, VA, 22161, USA.
PR: MF E02
DE: Environmental-aspects; Environmental-policy; Pollution-abatement; Waste-disposal.
DE: *Petroleum-industry-and-trade.
ID: Alberta-.
ID: *Foreign-technology.
AB: Regulation of solution gas flaring, traditionally undertaken for reasons of resource conservation, has become an increasingly important issue in Alberta due to environmental and health concerns. This publication describes and reports findings from a review of Alberta policies regarding solution gas flaring, or the burning off of gases dissolved in petroleum being produced at oil fields. The review included consultations with public and industry groups in areas of active solution gas flaring activity. Issues discussed include site-specific and regional environmental impacts, gas resource conservation, global environmental impacts, communication among industry, government, and the public, and regulatory efficiency. Existing policies regarding solution gas flaring are examined and recommendations for change are made where warranted. The appendix includes a brief economic analysis of the costs of further solution gas conservation in Alberta.

55 Estimating the Air Quality Impacts of Flare Operations.
AN: DE85016418XSP
CS: Performer: Oak Ridge National Lab., TN.
Funder: Department of Energy, Washington, DC.
RD: Jun 85. 10p.
NT: Air Pollution Control Association annual meeting and exhibition, Detroit, MI, USA, 16 Jun 1985, Paper No. 85-64.7.
PR: PC A02/MF A01
DE: Air-Quality; Carbon-Dioxide; Carbon-Monoxide; Diffusion-; Environmental-Impacts; Forecasting-; Nitrogen-; Plumes-; Waste-Disposal.
DE: *Flaring-; *Gaseous-Wastes; *Air-Pollution.
ID: ERDA/500200-; ERDA/010800-; ERDA/030800-.
AB: The body of information presented in this paper is directed to air quality planners and engineers who are interested in predicting the air quality impacts of proposed facilities using flares for pollution control devices. Available plume rise algorithms are used to compare predicted plume rise values for typical large and small commercial flares for a range of momentum effects and atmospheric stability conditions. It is found that buoyant flare plumes have the greatest potential for impact under unstable atmospheric conditions, in which the vertical motion of the atmosphere brings the flare emissions to ground level before appreciable dispersion has occurred. Plume rise and associated

ground-level concentrations from momentum-dominated flare plumes were found to be unaffected by stability conditions; the predicted pollutant concentrations (10 sup -5 g/m sup 3), and distances of the concentration from release point (less than 0.5 km), agreed with those for buoyant plumes under unstable conditions. In these cases, flare emissions could produce high ground level pollutant concentrations, depending on the emission rate. It is recommended that a flare plume rise field research program be initiated to better quantify flare plume rise and associated ground-level pollutant concentrations under various atmospheric conditions. (ERA citation 10:045081)
RN: CONF8506127
CN: Contract: AC0584OR21400

56 Investigation of Oil and Gas Well Fires and Flares. Final rept.
AN: PB94193976XSP
CS: Performer: Purdue Univ., Lafayette, IN. Thermal Sciences and Propulsion Center.
Funder: National Inst. of Standards and Technology (BFRL), Gaithersburg, MD.
RD: Jun 94. 68p.
NT: Sponsored by National Inst. of Standards and Technology (BFRL), Gaithersburg, MD.
PR: PC A04/MF A01
DE: Atomizers-; Soot-; Heat-flux; Burners-; Sprayers-; Mathematical-models; Jet-flow.
DE: *Natural-gas-wells; *Diffusion-flames; *Oil-wells; *Radiative-heat-transfer.
ID: Effervescent-atomization.
ID: *Well-fires; *Well-flares.
AB: A theoretical and experimental study of jet flames with applications to large fires resulting from oil well and gas well accidents is reported. The results have been used in the interpretation of the single point radiative heat flux data collected around well fires in Kuwait. Based on the high liquid loading involved in actual well fires, a new device called effervescent atomizer/burner was successfully designed, constructed and tested during the grant period. Measurements of flame heights, radiative heat loss fractions, emission temperatures, and path integrated transmittances were completed for nine crude oil and methane/air flames in the 10-20 KW range. The significant accomplishments during the grant include: (1) Development of a technique to find total radiative heat loss from turbulent jet flames based on measurements of heat flux at a single location; (2) Design and successful operation of an effervescent atomizer/burner. The burner also allows laboratory measurements of such flames for the first time; and (3) Study of global properties of the high liquid loading jet flames have shown that their lengths are affected by two-phase flow effects and that their soot loading and radiant output is lower than equivalent pool flames.
RN: NISTGCR94653
CN: Grant: NIST60NANB1D1172

57 Physical modeling of torch fires. An experimental study of large natural gas flames. Final report.
AN: DE92506313XSP
CS: Performer: Risoe National Lab., Roskilde (Denmark). Systems Analysis.
RD: 1991. 42p.

NT: Cover title: An experimental study of large natural gas flames.
AV: U.S. Sales Only.
PR: PC A03/MF A01
DE: Fire-Hazards; Heat-Transfer; Information-; Infrared-Thermography; Risoe-National-Laboratory; Temperature-Measurement; Thermal-Radiation; Wind-.
DE: *Natural-Gas; *Flames; *Flaring.
ID: EDB/034000-.
ID: *Foreign-technology.
AB: A natural gas flame test facility has been built at Risoe. Horizontal flames of length up to 8-10 meter (outflow 0.13 kg/s) can be produced. Two series of experiments have been conducted. In the first series free flames extending downwind were studied, and measurements included: temperature profiles in the flame, heat radiation to the surroundings and infrared thermography as well as background meteorology and outflow conditions. In the second series of experiments the net heat transfer to a cylindrical object placed vertically in the hottest part of the flame was measured using the (steel) cylinder as a calorimeter. The heat transfer was found to be largest on the front side facing the burner (up to 100 kW/m(sup 2)) and 2 to 3 times smaller on the back side. A database containing all measurements is abailable from Risoe.
RN: NEIDK784

58 Practical design of flare stacks
58.1 Kent, G. R.
1964 Hydrocarbon Processing, 43, 8 121-125

59 Levels of thermal radiation occurring on a marine petroleum production platform, emitted by a cantilevered flare
(NIVEIS DE RADIACAO TERMICA INCIDENTES NUMA PLATAFORMA MARITIMA DE PRODUCAO DE PETROLEO, EMANADOS DE TOCHA EM BALANCO)
59.1 BASTOS L E G; FILHO E C
BOL TEC PETROBRAS V 26, NO 3, PP 203-207, JULY-SEPT 1983 (IN PORTUGUESE)
(ISSN 00066117)
LANGUAGE: PORTUGUESE
For quantifying the levels of incidence of the thermal radiation emitted by a cantilever flare installed on an offshore platform, different parameters--such as emitted-radiation level, flame length, radiation center, its distance to the point of interest on the platform, and corresponding radiation shape factor--must be determined. This is accomplished with the aid of a model based on a formula giving the heat-flow density as a function of the different parameters. A computation algorithm in FORTRAN, allowing automatic determination of the radiation intensity at any point of interest on the platform, is developed. (17 refs.)

60 The heat of radiation of luminous flare flames
(DIE STRAHLUNGSWAERME LEUCHTENDER FACKELFLAMMEN)
60.1 BECKER R
CHEM ING TECH V 52, NO 2, PP 162-163, FEB 1980(II) (IN GERMAN)
ISSN 0009286X
LANGUAGE: GERMAN
The radiation heat of a flare flame determines the minimum height at which the flame must be for safety reasons. This radiation heat is determined in turn by the shape of the flame, the soot concentration, and the flame temperature. Empirical rules were used in the past. The problem is treated theoretically as if the flame were a surface radiator. Graphs compare the empirical and the theoretical results based on actual measurements, using acetylene as the test gas. Considering the flame as a point source of radiation yields maximum radiation values which are too low by a factor of up to 3. The treatment of the flame as a surface source yields satisfactory values for safety considerations, even if the unknown specific radiation is set at its maximum value of unity.

61 Developments in gas flaring systems
61.1 WEST F S
12TH ANNU SPE OF AIME ET AL OFFSHORE TECHNOL CONF PREPRINT NO OTC-3910,
PP 557-566 1980 (V 4)
LANGUAGE: ENGLISH
Developments in flare systems for the emergency depressurization of oil production trains on offshore platforms in the North Sea are reviewed in terms of safety, efficiency, cost, installation, and material usage. The most commonly used systems are enumerated and the fundamental requirements restated. Appraisal is made and notional costs are given of each type cited. API Guide RP521 rules for the calculation of radiation and temperature levels are examined and the extrapolations to them required for use on North Sea platforms stated. Structural problems in the design of lightweight structures subject to ice and high wind loadings are examined with regard to dynamic analysis of individual members, consideration of wake induced forces and shielding, the derivation of wind force spectrum from considerations of wind structures for inclusion in a dynamic analysis of complete structures, and selection of heat resistant materials in locations near the heat source.

62 Environmental guideline for the control of volatile organic compounds process emissions from new organic chemical operations
AS: National Work Group on the Control of Volatile Organic Compounds Process Emissions from New Organic Chemical Operations (Canada)
CS:National-Work-Group-on-the-Control-of-Volatile-Organic-Compounds-Process-Emissions-from-New-Organic-Chemical-Operations-Canada; Canadian-Council-of-Ministers-of-the-Environment
SE: Report
SD: Report / Canadian Council of Ministers of the Environment ; CCME-EPC-72E
SO: Winnipeg: Canadian Council of Ministers of the Environment, 1993. v, 39 p.Illustrations; Bibliography

PY: 1993
MN: 98-01434
NF: 1 fiche
AN: 3701631
AB: This guide has been developed for the control of volatile organic compound (VOC) process emissions from new organic chemical operations. Sections of the guide cover the following: applicability; definitions of terms; VOC emissions limits; total organic compounds monitoring; test methods and procedures, including emission rate calculations; and reporting and record keeping. The appendix includes requirements for flares used to control process emissions, sample reporting forms, and lists of organic compounds produced in the petroleum products, plastics/resins, and industrial organic chemical industries.
DE: Volatile-organic-compounds; Pollution-abatement; Chemical-industry,-Environmental-aspects
CL: Environment; Science; Non-depository-collections; Federal; Environnement; Sciences; Collections-nondeposees; Federal
IB: 1-895925-08-8
NT: On cover: CCME Management Plan initiative V303: 98-03041/1
LA: English
PT: Monograph; Monographie
UD: 19981200

63 Flare radiation estimated
63.1 McMurray, R
Kaldair Ltd, Feltham, England
Hydrocarbon Processing
November 1982,
pp175-181

64 Measurement of radiation heat flux from large scale flares
64.1 Bjorge T, Bratseth A
JOURNAL OF HAZARDOUS MATERIALS 46: (2-3) 159-168 APR 1996
Abstract: Measurements of radiation heat flux are performed on two oil rig flares in order to estimate the capacity of the flares, One measurement series is also conducted on a flare in a gas processing unit on shore for the same purpose. The results are compared with estimates using an empirical model for radiation from flares. The measured radiation heat flux levels ranged from 0.8 to 4.2 kW/m(2), depending on the location of the measurement point and on mass flow of gas (16.9-90 kg/s), wind velocity and wind direction, All sensors were located between 120 and 150 m from the estimated flame centre of the flare, on the main platform. Comparisons between computations with an empirical model and the measurements were in reasonable agreement (-10-+35%). If the water content of the air is taken into considerations, the discrepancy is between -33 and -6%.
Author Keywords:safety, flare, radiation, measurements
Addresses:Bjorge T, SINTEF, NTH, APPL THERMODYNAM, TRONDHEIM, NORWAY. STATOIL, N-4001 STAVANGER, NORWAY.

Publisher:ELSEVIER SCIENCE BV, AMSTERDAM
IDS Number: UC600
ISSN: 0304-3894

65 Large-scale free and impinging turbulent jet flames: Numerical modelling and experiments

65.1 Johnson AD, Ebbinghaus A, Imanari T, Lennon SP, Marie N
PROCESS SAFETY AND ENVIRONMENTAL PROTECTION
75: (B3) 145-151 AUG 1997

Abstract: This paper summarizes progress in the development and validation of a suite of computational fluid dynamics sub-models for the calculation of open air and impinging turbulent gas jet flames. The sub-models are implemented in the commercial flow and radiative heat transfer solvers CFX-FLOW3D and CFX-RADIATION. Demonstration calculations are reported for an open air sonic 0.3 propane flame, and a 2.5 subsonic natural gas flame in the open air and impinging on a 2 m diameter cylindrical target. Improvements for the calculation of under-expanded jet shock structures, flame Lift-off, and combustion in the main bulk of the flame are reported. A practical model for predicting convective heat transfer is identified. Results of preliminary calculations of flame impingement heat transfer are present.

Author Keywords:CFD, jet-flame impingement, heat transfer
KeyWords Plus:THERMAL-RADIATION
Addresses:Johnson AD, SHELL RES & TECHNOL CTR, POB 1, CHESTER CH1 3SH, CHESHIRE, ENGLAND.
Publisher:INST CHEMICAL ENGINEERS, RUGBY
IDS Number:XR711
ISSN:0957-5820

66 Comprehensive modeling of turbulent flames with the coherent flame-sheet model .2. High-momentum reactive jets

66.1 Beeri Z, Blunsdon CA, Malalasekera WMG, Dent JC
JOURNAL OF ENERGY RESOURCES TECHNOLOGY-TRANSACTIONS OF THE ASME
118: (1) 72-76 MAR 1996

Abstract: This paper describes the application of computational fluid dynamics (CFD) to the prediction of the characteristics of high-momentum vertical and horizontal flames in ambient airflows. The KIVA-II code has been modified by extending the range of boundary conditions and by the addition of the following I a version of the coherent flame-sheet model, Tesner's soot generation and Magnussen's soot oxidation model, and an implementation of the discrete transfer radiation model. To assess the accuracy of the complete model for prediction purposes, results are compared with experimental data. Predictions of temperature and flame profiles are in good agreement with data while predictions of radiative heat transfer are not entirely satisfactory.

KeyWords Plus: CROSS-FLOW, DIFFUSION FLAMES, CONCENTRATION FIELD, PREDICTIONS, FLARES, WIND
Addresses: Beeri Z, LOUGHBOROUGH UNIV TECHNOL, DEPT MECH ENGN, LOUGHBOROUGH LE11 3TU, LEICS, ENGLAND.

Publisher:ASME-AMER SOC MECHANICAL ENG, NEW YORK
IDS Number: UD463
ISSN: 0195-0738

67 Investigations of Flare Gas Emissions in Alberta
67.1 Strosher, M
Environmental Technologies, Alberta Research Council, November 1996, Project number 5552

68 Improve flare management
68.1 Knook-C
HYDROCARBON-PROCESSING.NOV 1997; 76 (11) : 49-50.
PY1997
IS0018-8190
CCEngineering-Computing-and-Technology
UD199700 .

69 A preliminary study into the relationships between thermal radiation and plume rise
69.1 Leahey, D. M.
PUBLISHED: Edmonton : Alberta Environment, May 1979
PAGING: 33 p
SUBJECTS: Smoke plumes. Air--Pollution--Mathematical models
NOTES: Funded by Alberta Environment, Research Secretariat.
Bibliography: p. 33

70 A preliminary study of the chemical composition and combustion efficiency of a sour gas flare
PUBLISHED: Edmonton, Alta. : Research Management Division, Alberta Environment, 1985.
PAGING: x, 93 p. : ill. ; 28 cm.
SERIES: RMD (Series) ; 85-30.
SUBJECTS: Natural gas--Analysis. Flare gas systems (Chemical engineering)
BIBLIOGRAPHY: Includes bibliographical references.
Book

71 Field study of plume rise and thermal radiation from sour gas flares
71.1 M.J.E. Davies, D.M. Leahey
PUBLISHED: [Edmonton] : Alberta Environment, 1981.
PAGING: viii, 46 leaves : ill. ; 28 cm.
SUBJECTS: Plumes (Fluid dynamics) Natural gas.
NOTES: Prepared for Alberta Environment and the Alberta Energy Resources Conservation Board.

72 Evaluation of the efficiency of industrial flares : H2S gas mixtures and pilot assisted flares

72.1 Pohl, J. H. ,Soelberg, N. R.
Prepared for the Energy and Environmental Research Corporation
Air and Energy Engineering Research Laboratory
Energy and Environmental Research Corporation
Published: Research Triangle Park, N.C. : Air and Energy Engineering Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency ; Springfield, Va. : NTIS (distributor), Sept. 1986
Subject: Flare gas systems (Chemical engineering) --Evaluation Waste gases -- Combustion.
Note: |PB87-102372. -- |EPA/600/2-86/080. -- Includes bibliographical references

73 Removal of liquid from solution gas streams directed to flare and development of a method to establish the relationship between liquids and flare combustion efficiency

73.1 Mel Strosher, Allan K. Chambers and Gary Kovacik.
prepared for: Alberta Environmental Protection ; Alberta. Alberta Environmental Protection. Environmental Sciences Division.
Published: Edmonton : Alberta Environmental Protection, Environmental Services, Environmental Sciences Division, 1998. Series: Pub. No. T/448
Subject: Flare gas systems (Chemical engineering) --Alberta. , Waste gases --Alberta – Combustion, Gas industry --Environmental aspects --Alberta.
Material: vi, 34 p. ; 28 cm.
ISBN: 077850591X

74 The efficiency of flares in cross-winds

74.1 Skinner, George Alexander
University of Alberta.
Dept. of Mechanical Engineering.
Published: 1998.
Material: 132 leaves ; 29 cm.
Thesis (M.Sc.)--University of Alberta, 1998.
System ID no:ANH-6809

75 Management of routine solution gas flaring in Alberta : report and recommendations of the Flaring Project Team.

75.1 Flaring Project Team. - Clean Air Strategic Alliance
Published: Edmonton : Clean Air Strategic Alliance, [1998]
Subject: Waste gases --Alberta --Combustion. Flare gas systems (Chemical engineering) --Alberta.
1 v. : ill., maps ; 30 cm.
June 1998.
Photocopy. iii, 25 p.

76 Radiant heating from flares
76.1 Brzustowski, TA, Gollahalli, SR, Gupta, MP, Kaptein, M, Sullivan, HF
ASME paper 75-HT-4 (1975)

77 Radiative energy transfer from turbulent diffusion flames
77.1 Markstein, GH
Technical report
FMRC Serial Number 22361-2 Factory Mutual Research Corp, 1975
Also ASME paper 75-HT-7 (1975)

78 Flare system design simplified
78.1 Tan, S.H.
Hydrocarbon Processing
46 1 172-176

79 How to design a safe flare stack (part 1)
79.1 Hajek, J.D. and Ludwig, E.E.
Petro/Chem Eng.
June C31-C38 1960

80 How to design a safe flare stack (part 2)
80.1 Hajek, J.D. and Ludwig, E.E.
Petro/Chem Eng.
July C44-C51 1960

81 Radiative transfer
81.1 Hottel, Hoyt C. (Hoyt Clarke), 1903-
PUBLISHED: New York, McGraw-Hill [1967]
PAGING: xxiv, 520 p. illus. 24 cm.
SERIES: McGraw-Hill series in mechanical engineering.
SUBJECTS: Radiative transfer
OTHER ENTRY: Sarofim, Adel F. joint author.

82 Furnace operations
82.1 Reed, Robert De Hart, 1905-
EDITION: 3d ed.
PUBLISHED: Houston : Gulf Pub. Co., Book Division, 1981.
PAGING: ix, 230 p. : ill. ; 26 cm.
SUBJECTS: Furnaces, Oil burners
BIBLIOGRAPHY: Bibliography: p. 198.

83 Engineering data book / published as a service to the gas processing and related process industries

EDITION: 10th ed.
PUBLISHED: Tulsa, Okla. : Gas Processors Suppliers Association, c1987-
PAGING: v. : ill. ; 30 cm.
SUBJECTS: Gas manufacture and works--Equipment and supplies--Handbooks, manuals, etc.
NOTES: 1935 ed. entered under: Natural Gas Processors Suppliers Association and has title: Engineering

84 Equipment design handbook for refineries and chemical plants

84.1 Evans, F. L. Jr.
2, Gulf Publishing Co., Houston, Texas, 1974
(from Pavel paper – offers synthesis of Tan and Kent methods)
ISBN: 0872012549 (v. 1)

85 Total Emission of Soot and Thermal Radiation by Free Turbulent Diffusion Flames

85.1 Becker, H. A. and Laing, D.
Combustion and Flame 1981

86 The turbulent diffusion flame in a cross-wind

86.1 Brzustowski, T. A.
Proceedings of the 5th Canadian Congress of Applied Mechanics, Fredericton, May 26-30, 1975.

87 Predicting Radiant Heating from Flares

87.1 Brzustowski and Sommer
AMERICAN PETROLEUM INSTITUTE
PROCEEDINGS: API Division of Refining (Washington DC)

88 Designing Flares for Enhanced Service Life

88.1 Keller, M and Smith, S
Presented at a Seminar arranged by the Canadian Gas Producers Association
June 1983

89 Flare Radiation Prediction: A Critical Review

89.1 Schwarts, R. E. and White, J. W.
30th Annual Loss Prevention Symposium, Session 12, Feb 28 1996

90 Soot Formation in Weakly Buoyant Acetylene-Fuelled Laminar Jet Diffusion Flames Burning in Air

90.1 Sunderland, P. B., Koylu, U. O. and Faeth, G. M.
Presented at the Twenty-Fifth Symposium (International) on Combustion, Irvine, California, 31 July – 5 August 1994

91 Cost-effectiveness of an ultrasonic flare-gas monitoring system

91.1 Michel Franco

Flaring Technology Symposium, Environmental Services Association of Alberta, Grant MacEwan Com. Col., Edmonton, Alberta, 1996.

92 Flaring in hostile environments

92.1 Schwartz, R and Keller, M

Presented at a seminar on flare systems, arranged by the Norwegian Society of Chartered Engineers, date unavailable.

93 An experimental analysis of flame stability of open air diffusion flames

93.1 Noble, Keller, Schwartz

Presented at the American Flame Research Committee, 1984 International Symposium on Alternative Fuels and Hazardous Wastes, October 9-11 1984, Oklahoma.

94 Flare System Design

94.1 Swander and Potts

Presented at an American Petroleum Institute Seminar, Fundamental Applications of Loss Prevention, Texas, October 15, 1986.